



The integration of human factors, operability and personnel movement simulation into the preliminary design of ships utilising the Design Building Block approach.

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## Declaration

I, Lorenzo Casarosa, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signed:

Date:

“An expert is someone who knows more and more about less and less, until he knows everything about nothing.”

*Mahatma Gandhi*

## Abstract

This thesis presents the feasibility, advantages and impact on Preliminary Ship Design of an approach to integrate ship configurational design with the modelling and simulation of a range of crewing issues, such as operations and evacuation. Integrating personnel movement simulation into preliminary ship design introduces the assessment of onboard operations at the front-end of the design process, informing the design and enabling improved operability while the design is still amenable to changes. The approach to accomplish this integration is discussed with the aim of informing all parties involved in the design of ships with regard to the main aspects of personnel operability and on board safety.

The research was undertaken as part of a three years research project funded by the Engineering and Physical Sciences Research Council (EPSRC) entitled “Guidance on the Design of Ships for Enhanced Escape and Operation”. The project aimed at bringing together the University of Greenwich developed “maritimeEXODUS” personnel movement simulation software and the SURFCON implementation in the PARAMARINE suite of the Design Building Block approach to Preliminary Ship Design, which originated with the UCL Ship Design Research team.

The approach and procedural implications of integrating personnel movement simulation into the preliminary ship design process are presented through a series of SURFCON ship design case studies. With the UK Ministry of Defence as the industrial partner to the project, this study on “design for operation” concentrates on naval vessels, which provide excellent examples of complex environments. Design studies, based on the Royal Navy Type 22 Batch III Frigate design, were analysed using PARAMARINE, maritimeEXODUS and bespoke interface software produced by the candidate. Technical aspects of the development of the interface software are discussed from a procedural perspective, focusing on integration and usability issues. The discussion addresses alternative options to visualising the simulation results and how to integrate into a ship design model a minimum level of detail sufficient to conduct simulations able to inform the designer, while retaining the flexibility the design requires in early stages design.

The thesis concludes by summarising the opportunities that integrating operational simulation into preliminary ship design opens up for the future practice of ship design, contributing to the debate on the nature of ship design and of Computer Aided Preliminary Ship Design.



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## Nomenclature

2D	2 Dimensional
3D	3 Dimensional
AAW	Anti-Air Warfare
ANFL	Automatic Node Flood Operation (maritimeEXODUS' functionality)
ANN	Artificial Neural Network
ARPA	Advanced Research Projects Agency
ASCII	American Standard Code for Information Interchange (plain text files)
ASNE	American Society of Naval Engineers
BL	Baseline (design)
CAD	Computer Aided Design
CAGPSD	Computer Aided Graphical Preliminary Ship Design
CAGSD	Computer Aided Graphical Ship Design
CAM	Computer Aided Manufacture
CASD	Computer Aided Ship Design
CFD	Computational Fluid Dynamics
CI	Connectivity Items
CIWS	Close In Weapon System
CO	Commanding Officer
COTS	Commercial Off-The-Shelf (products)
CPO	Chief Petty Officer
CSV	Comma Separated Variable (basic file format for numerical data)
DBB	Design Building Block
DBBa	Design Building Block approach
DBBh	Design Building Block hierarchy
DCFFP	Damage Control and Fire Fighting Party
DE&S	Defence Equipment and Support
DoD	Department of Defence (USA)
DRC	Design Research Centre (see UCL DRC)
DWG	DraWinG (CAD programs filename extension)
DXF	Drawing (file) eXchange Format
EGO	Evacuation Guidance and Operations
EI	Equipment Items
EMS	Emergency Scenario
EPSRC	Engineering and Physical Sciences Research Council
ES	Evaluation Scenario
FEA	Finite Element Analysis
FSEG	Fire Safety Engineering Group (University of Greenwich)
GA	General Arrangement (drawings)
GIF	Graphic Interchange Format (file extension)
GRC	Graphics Research Corporation Ltd.
GUI	Graphical User Interface
HF	Human Factors
HMEDC	Hull, Mechanical, Electrical & Damage Control
HPM	Human Performance Metric (or Metrics)
HPMx	Human Performance Matrix (nested table of HPM values)
HR	High Resolution (model)
IJME	International Journal of Maritime Engineering

IMarEST	Institute of Marine Engineering, Science & Technology
IMDC	International Marine Design Conference
IMO	International Maritime Organisation
INEC	International Naval Engineering Conference
IPDE	Integrated Product Data Environment
IPM	Integrated Product Model
ISO	International Organization for Standardization.
JPG	Joint Photographic (experts) Group (format for image storing)
JPG or JPEG	Joint Photographic Experts Group (a compressed graphics format suitable for static images)
JR	Junior Rate
KCL	Kernel Command Language (PARAMARINE's file extension)
LCS	Littoral Combat Ship (US Navy 2000's project)
LPD(R)	Landing Platform Dock (Replacement) - (UK project)
LR	Low Resolution (model)
MoD	Ministry of Defence (UK)
MPEG	Moving Picture Experts Group (ISO file format for video compression)
MR	Medium Resolution (model)
MS Excel	Microsoft Excel
MTA	Meta-data (maritimeEXODUS scenario file extension)
NBC	Nuclear, Biological and Chemical
NBCD	Nuclear, Biological and Chemical Defence
NCHPM	Naval Combatant Human Performance Metrics
NFL	Node Flood Operation (maritimeEXODUS' functionality)
NMTA	New Meta-data (new EXODUS' MTA file extension)
NOP	Normal Operational Procedures (non-emergency scenarios)
OPS	Operations (Warfare Operations)
PBD	Performance Based Design
PDM	Physical Data Model
PDMS	Plant Design Management System
PIM	Product Information Model
PLM	Product Lifecycle Management
PM	Performance Measures
PMS	Personnel Movement Simulation
PO	Petty Officer
PSD	Preliminary Ship Design
RCS	Radar Cross Section
RINA	Royal Institution of Naval Architects
RN	Royal Navy (UK)
SBD	Simulation Based Design
SDE	Ship Design Exercise (see UCL SDE)
SESea	Sea Systems Group (former SSG)
SIM	Spatial Information Management
SPM	Smart Product Model
SSes	Surface Ship Engineering Standards
SSF	Scenario Specification File
SSG	Sea Systems Group (MoD Procurement Agency, now SESea)
STG	Sea Technology Group (now SSG)
SUBCON	Submarine Concept Design System

SURFCON	Surface Concept Design System
SWATH	Small Waterplane Area Twin Hull (ship)
UCL DRC	University College London, Design Research Centre
UCL SDE	University College London, Ship Design Exercise
UoG	University of Greenwich
VB	Visual Basic (programming language used also in Microsoft Excel)
VP	Vessel Performance (numerical score)
VR	Virtual Reality
VRML	Virtual Reality Mark-up Language
W&SB	Watch and Station Bill
WMV	Windows Media Video (video compression format)
WRL	Web Rule Language (VRML file extension)
WT	Water Tight (integrity)
WTC	Water-Tight Compartment
WTD	Water-Tight Door
XML	eXtensible Mark-up Language

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# **1 - Introduction**

## **1.1 Preamble**

This thesis investigates and describes an innovative approach to ship design for operation which integrates human factors, operability and personnel movement simulation into the design process. It concentrates on integrating operational issues in preliminary ship design and on the implications on the design process undertaken using the UCL approach to preliminary ship design, namely the Design Building Block approach [Andrews and Pawling, 2003]. This thesis illustrates the feasibility of such an approach to ship design through the production of a series of SURFCON ship designs, based on the Royal Navy Type 22 Batch III Frigate design and their analysis using the software tools PARAMARINE and maritimeEXODUS together with a set of software tools developed by the candidate as part of this research. This thesis also presents the background research and the interfacing of these tools from both a technical and procedural perspective and the procedure and the relevant guidance developed to enable the proposed approach, and the related software tools, to be applied to the early stage design of ships.

The discussion focuses on the approach and procedural implications of the integration of personnel movement simulation into the preliminary ship design process. The lessons learnt from this research contribute to the ongoing debate on the nature of the ship design approach and of Computer Aided Preliminary Ship Design and on how best to foster an ability to undertake and then manage engineering design [Wallace, 2005, Nowacki, 2009 and RAENG, 2010].

The thesis draws conclusions on the scope that integrating personnel movement simulation into preliminary ship design opens up for the future practice of ship design and concludes by summarising new areas for possible further research that could be pursued.

## **1.2 Scope and aim of the thesis**

### **1.2.1 Research scope**

The research on the integration of personnel movement simulation into ship design outlined in this thesis is focused on preliminary stages of the ship design process, when a wide range of concepts and solutions are being investigated by the designer. This thesis does not cover issues of contract design or detailed production design, where the selected design solution is developed to a very high level of detail.

The general focus is on surface warships, although the proposed approach and the issues highlighted in this thesis could be applicable to preliminary design of any other type of ship and of other enclosed environments where complex personnel operations take place. This thesis proposes future research streams, new software development and key principles in the integration of personnel movement simulation into computer aided preliminary ship design that could enhance the effectiveness of the Design Building Block approach.

Although the proposed integrated approach is generic in nature, its development is initially focused on naval vessels to demonstrate a proof of concept against a set of demanding ship operations, which are not limited to the simulation of personnel evacuation largely used to date after the preliminary stages of ship design. The research concentrates, specifically, on frigate type surface combatants and the target vessel selected as a base-line ship design by the industrial partner, the Sea Systems Group of the UK MoD, is the Royal Navy Type 22 Batch III Frigate.

This thesis considers the feasibility of advantages for and impact on Preliminary Ship Design (PSD) of an approach that integrates ship configurational design with the modelling and simulation of a range of personnel movement issues, such as

operations and evacuation. Preliminary ship design, encompassing the terms defined by Andrews [1994] as Concept Exploration, Concept Studies, Concept Design and early Feasibility Design, is intended as the earliest stage of ship design characterised by the exploration of options and investigation of design drivers and relationships. At this stage the design is not rigidly defined and so a wide range of studies could be carried out, not only giving the opportunity for innovative and creative solutions to be investigated, but also allowing the requirements to be subject to investigation and change as the nature of possible solutions becomes known. As such, preliminary ship design could require few resources and little cost, but could have a very significant impact on the final configuration and cost of the vessel.

Integrating personnel movement simulation into preliminary ship design permits the assessment of specific onboard operations at the front-end of the design process. The research conducted on this proposed integration, included investigating how it could be most effectively achieved by informing the designer when the design is still amenable to significant change, and by prompting the designer with the necessary information to decide if and how to modify the design in order to improve its operability.

The research was undertaken as part of a three year research project funded by the UK Engineering and Physical Sciences Research Council (EPSRC) entitled “Guidance on the Design of Ships for Enhanced Escape and Operation” [Galea and Andrews, 2004]. This was a joint project between the Fire Safety Engineering Group (FSEG) at University of Greenwich (UoG) and the DRC in the Department of Mechanical Engineering at University College London (UCL).

The project aimed at bringing together the UoG developed “maritimeEXODUS” [Galea et al., 2003] simulation software and the SURFCON implementation in the PARAMARINE suite of the UCL Design Building Block approach to Preliminary Ship Design.

The work undertaken in the EPSRC funded research project produced a novel approach to ergonomic design, software tools to interface maritimeEXODUS and PARAMARINE and examples of the application of “design for operation”. The example area of research application was that of naval combatants since such vessels provide environments in which complex personnel operations take place in a relatively confined and densely packed spaces.

The research also addressed the impact on the procedural approach to ship design of such an integration of simulation techniques in early stage design by considering the interdependence between the type of simulations used and the point in the design process they are undertaken. Despite the focus of the research, the conclusions of this thesis are considered to be of wider applicability. Given the complexity of ships and the characteristics of the design process, the wider applicability of the approach proposed is considered after the demonstration has been presented. If the proposed approach to this integration proves to be feasible in the case of the ‘case studies’ addressed in this thesis, then this same approach could be considered, in a broader perspective, for its possible application to other design domains. Designing ships, in fact, is such a wide-ranging process that could be seen as representing one of the most comprehensive ways of approaching other engineering design typologies.

### **1.2.2 Research aims**

The aim of the research was the investigation of the integration of the leading technologies of personnel movement simulation and ship configurational design. The feasibility of such integration, together with evaluating its advantages and discussing its impact on the Preliminary Ship Design (PSD) process was undertaken.

Thus the simulation of the movement of the on-board crew during relevant evolutions was considered. The evolutions range from normal operations to emergency scenarios and from peacetime procedures to combat operations.

The research on the integration of the simulation of personnel movement during these evolutions with the Design Building Block approach to preliminary ship design, aimed to produce insights on the nature of the design process arising from the implementation of this integration. Directions for future developments of the design process are proposed which would enhance the effectiveness of the Design Building Block approach in the elucidation of the problems presented by preliminary design and in developing the design solutions.

The high level objective of the research is to show the feasibility of the integration of simulation analysis with the DBB approach and to show the impact of integrating personnel movement simulation and Computer Aided Preliminary Graphical Ship Design (CAGPSD). The results of this integration are expected to benefit all parties involved in ship design, construction and operation. The approach followed in the thesis is intended to inform all parties involved in the design of ships with responsibilities for operability and onboard safety.



### **1.3 Structure of the thesis**

The thesis is divided into six chapters and is complemented by separate appendices providing additional material relevant to specific sections and therein referred to. The appendices include (in Appendix G.1 and G.2), two published papers which the candidate co-authored with his supervisor and colleagues.

Chapter 1 describes the context for this thesis and described its scope and aims. Chapter 2 provides background for this thesis considering the nature ship design, approaches to computer aided preliminary ship design and the integration of simulation in computer aided engineering design both in general and then in the ship design process.

Chapter 3 outlines the work done in developing of the integration of personnel movement simulation in preliminary ship design. This chapter focuses on the technical, procedural and software integration of PARAMARINE-SURFCON and maritimeEXODUS and on the implications for the design process.

Chapter 4 describes examples of the application of the approach, illustrates the range of investigations carried out using the tools and methods developed and shows the results obtained.

The discussion in Chapter 5 brings together the approaches outlined in Chapter 2 with the procedure and the tools described in Chapter 3 and the experience of applying the proposed approach described in Chapter 4.

From these discussions, conclusions are drawn and presented in Chapter 6 together with suggestions as to how the research could be continued and its scope further extended.

As mentioned in Section 1.2.1, the research described in this thesis was part of a three years research project funded by the Engineering and Physical Sciences Research Council. That project brought together the University of Greenwich developed maritimeEXODUS personnel movement simulation software and the SURFCON implementation in the GRC<sup>1</sup> Ltd. PARAMARINE ship design suite of the Design Building Block approach to preliminary ship design. The Design Building Block approach originated with the UCL Ship Design Research team and is described in by Andrews [2003a]. The SURFCON ship design tool and the DBB approach are used to provide an integrated representation of the spatial model of the design configuration at the earliest stages of the design process. Varied approaches to achieve this integration of maritimeEXODUS and SURFCON have been investigated with the aim of enhancing the guidance for all parties involved in the design, regulation, construction and operation of ships with regard to the main aspects of operability and on board safety.

This thesis addressed how to model, integrate and incorporate into preliminary ship design, a sufficient level of detail to conduct an analysis of the ergonomic features relevant to the simulation of personnel evacuation and operability, while retaining the flexibility of early stages design. Flexibility of early stages design, as well as that of a design process in general, is the characteristic that allows design solutions to be readily adapted to changing conditions and meet a ranged set of design requirements [Chen and Yuan, 1998].

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<sup>1</sup> Graphic Research Corporation Limited - [www.grc-ltd.co.uk](http://www.grc-ltd.co.uk)

## 2 - Research background

This chapter outlines the background for this thesis considering the nature ship design, approaches to computer aided preliminary ship design and the integration of simulation in computer aided engineering design both in general and in the ship design process.

The background and context of the research presented in this thesis are presented in Section 2.1, while Section 2.2 addresses issues relevant to Human Factors integration in Preliminary Ship Design and introduces the concepts of Micro and Macro ergonomics.

Section 2.3 clarifies the meaning and use of simulation in design and Section 2.4 gives an account of the evolution of CAD systems and their use in Preliminary Ship Design and how this lead to the development of Computer Aided Graphical Preliminary Ship Design (CAGPSD) systems.

Section 2.5 describes the rationale behind the use of simulation techniques and Simulation Based Design methods in ship design focusing, in particular, on escape/egress simulation in maritime applications and on the simulation software used in the research: maritimeEXODUS.

Section 2.6 describes the considerations relevant to the approach to the integration of CAGPSD and personnel movement simulation and Section 2.7 provides an overview of the available software tools for ship design and Personnel Movement Simulation (PMS) integrated by examples and brief descriptions of a representative selection of the most common tools in Appendix A.

## 2.1 Background

The research extends the comprehensive approach to initial design of ships (and other complex systems) developed by Andrews [1981, 1984, 1986, 1987, 1998] at UCL and implemented by Dicks [Andrews and Dicks, 1997 and Dicks, 1999] and Pawling [Andrews and Pawling, 2003; Andrews and Pawling, 2006a and Pawling, 2007]. Figure 2.1.1 gives a simplified history of the application of the Design Building Block approach to design. The need for a new approach to ship design, integrating architectural issues at the earliest stages, was proposed by Andrews in 1981 [Andrews, 1981]. This proposal considered the wider issue of the philosophy of design and outlined a new approach to PSD. The philosophical and practical issues were discussed along with a first demonstration of the integration in much more detail in Andrews' subsequent thesis [Andrews, 1984] and summarised in [Andrews, 1986 and Andrews, 1987]. In these, Andrews proposed a more holistic approach to ship design with a completely integrated architecturally centred synthesis process, including spatial layout, with the numerical balance process rather than the traditional sequential ship design processes.

The UCL Design Building Block (DBB) approach to preliminary ship design is a holistic and creative approach to the initial design of physically large and complex products and has been incorporated in the commercially available PARAMARINE [Munoz and Forrest, 2002] ship design system through a module entitled SURFCON. The research presented develops and extends the applicability of the approach to integrating a personnel simulation capability into the DBB approach and demonstrates how the DBB approach could be enhanced and so bring novel and significant insights into the design process in its earliest stages.

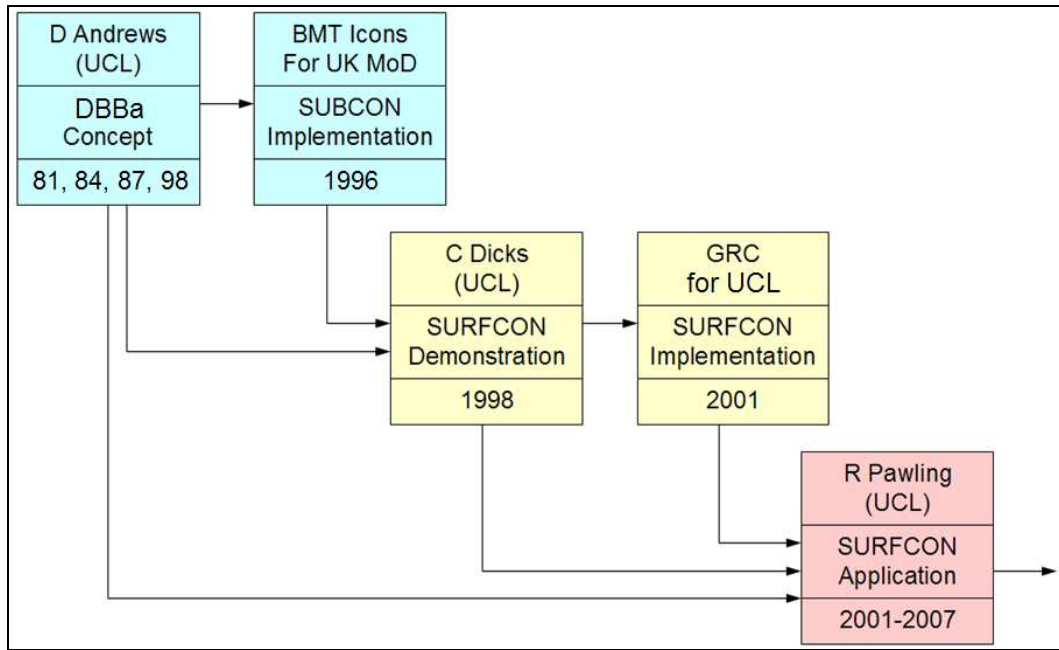


Figure 2.1.1 - The development and implementation of the UCL Design Building Block Approach.

The research programme in the DRC continues the investigation into the nature of the design of large and complex entities, which has been termed ‘Design on a Grand Scale’<sup>2</sup>, and into how the ever increasing capacity of computers and the evolution of software tools capabilities have radically altered and are continuing to reshape design practice. Moreover, by regarding ship design as an example of made to order design<sup>3</sup>, the UCL research provides insights relevant to a more general understanding of design philosophy and design methodologies.

An aspect opened up by the architecturally centred DBB approach is that of simulation tools which require the internal configuration of the ship in order to be performed. A significant area of investigation is that of personnel movement and it is this that the current research addresses. This was seen to be beneficial as it would allow to bring major issues (for example those related to style, operations

<sup>2</sup> “Design on a grand scale” was coined by G. H. Fuller in his written discussion to Andrews’ paper on “Creative Ship Design” [Andrews 1981].

<sup>3</sup> “Made-to-order” products is a term coined by the Engineering Design Centre (EDC) team at Newcastle University led by Prof W Hills [Cleland and Hills 1994]

and ergonomics) to the fore of the design process when it is still feasible to take these issues into consideration given the open nature of a design at the preliminary phase where the cost implications are much lower than those of modifying the design later.

The research has largely focused on the earliest stages of ship design as they could be considered the most crucial design stages in terms of the consequences of any decision taken (e.g. evacuation, producability and adaptability). The basis for this focus is that there are many issues that are currently only assessed after the preliminary design stages of a ship design and the design is essentially defined. Other UCL DRC projects, have already investigated and demonstrated the benefits of applying the DBB approach to other concerns in ship design (e.g. producability) [Andrews et al., 2006]. The research investigates the possibility of assessing personnel movement aspect of operability at the earliest design stages using enhanced simulation tools, seamlessly integrated in the design process. In particular, consideration has been given to introducing ship organisational and operational perspectives into initial design.

The emphasis on the Human Factors (HF) dimension is vital to the design of technically complex and physically large design products, such as naval vessels, but is rarely given sufficient prominence in the crucial formative stages of large-scale design because of the inherent difficulties in doing so. This could be mainly attributable to the significant difference between the level of detail required by HF analyses and that, which is typically adopted in the early design stages. This, HF analysis requires a high level of detailed design definition to be able to produce meaningful results, while early stages design activities

require, in comparison, a low level of definition to allow quick reconfiguration of the design. The concept or initial design phase, in fact, can be highly characterised by dynamic periods where the principal features and dimensions of a ship are subject to frequent changes in the designer's search for a good balance between the different design requirements.

The possibility of addressing human factors aspects in early stage design is attractive because these issues could have significant downstream implications in the design, particularly so in designing physically large and organizationally complex systems. The proposed integration of personnel movement simulation with Computer Aided Preliminary Ship Design (CASPD) enables many human factors issues to be given more appropriate prominence.

As mentioned in Section 1.2.1, the research was funded by the UK EPSRC as a joint project between UCL and UoG aimed at interfacing maritimeEXODUS with SURFCON to provide initial design guidance to ship designers on personnel movement integration in preliminary ship design. In addition, the research also aimed at investigating the wider ship design implications and the advantages of integrating the simulation tools into Computer Aided Graphical Preliminary Ship Design (CAGPSD). These themes are addressed in the next sections, illustrated with examples in Chapters 3 and 4 and discussed in Chapter 5.

## **2.2 HF and preliminary ship design (PSD)**

To understand the role that human factors engineering might and indeed should, play in preliminary ship design, it is necessary to set some boundaries on what is being addressed by the term preliminary ship design and what is intended by the

application of human factors issues in the context of the preliminary design of physically large and complex entities such as naval combatants.

Ship design, has been stated to be a paradigm for the design of other large complex constructions [Andrews, 1998]; this is because of the characteristics of ships as physically large, multi-role, self-sufficient, inhabited (with high density) and mobile environments, together with the peculiar nature of their made-to-order and politicized design process. Design on such a grand scale with a high degree of inherent complexity, involves the assembly of a multitude of interacting and interdependent subsystems and the necessity to compromise between a wide variety of specific requirements, which are often conflicting therefore requiring tailored engineering solutions.

As an example of the complexity levels of the investigation in the research, some of the main characteristics typical of combatant ships are listed below:-

1. Technology dense,
2. Equipment rich,
3. Operationally intensive,
4. Hazardous enclosures (e.g. fuel tanks and ammunition storage)
5. Potential targets during war and terrorist attacks,
6. Inhabited (with high population density),
7. Mobile and self-sufficient,
8. Physically large, but confined enclosures,
9. Versatile and multi-role (changing scenarios and theatres of operation),
10. Adaptable and usable in unforeseen roles,
11. Used in extremely variable environmental conditions,
12. Subject to rapid obsolescence (e.g. strategical and technological),
13. Maintainable and upgradeable in time (systems, sub-systems and layout),
14. Very expensive (e.g. design, manufacturing and through life costs).



In addressing the inherent complexity of ships Andrews [1998] also drew attention to the fact that the overall design process and, importantly, the initial design synthesis, is not a single invariant process common to all ships or other complex entities. This is true even when considering each of the intermediate steps and iterations constituting the design process. For example, even restricting the focus of the application of simulation techniques to the initial design of large scale products, it is difficult to recommend the use of a single simulation method with generic validity and applicability to a whole range of similarly large and complex entities. This reinforces the need to consider the applicability of simulation techniques to preliminary design and to give proper consideration to the scope and applicability of integrating simulation in preliminary ship design as is proposed in this thesis.

The technical complexity of ships and their design process is comparable to the computational complexity of software packages used to perform simulations (intended in their connotation of generic engineering simulations used to undertake simulation of engineering performance – e.g. Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD)) and to the procedural aspects of the use of such software. This is particularly true when considering software used to perform personnel movement simulation.

In general, computer-assisted simulation tools reproduce a system in a digital model, analyse its behaviour over a certain domain (usually, time) and in a definite dimension (i.e. taking into account a limited number of factors) by understanding the interactions between the model's components. Simulation, in this context, gives the opportunity of understanding, forecasting and controlling, as well as

undertaking trial-and-error studies on a model in a risk free environment. This represents a significant advantage for many disciplines as it provides the insight into the way a system will behave before it is actually built and without the need to produce a physical prototype. In several fields (e.g. industrial scale product design) simulation leads to significant benefits when compared to the use of prototypes (e.g. eliminating the cost of building and testing prototypes), in some other it may be indispensable in achieving the desired level of confidence in the design (e.g. consumer products). The benefits of using simulation are even more evident in the case of design on a grand scale and, for example, of the marine industry, where the construction of a full scale prototype is economically rarely justified.

There is also a need to consider how and when to undertake simulation in design which is a particularly relevant matter when considering this step in the context of HF simulation and preliminary design. Aside from considerations of verification of compliance with standards and regulations, the decision to apply simulation tools to the design model, in general, could be seen as being governed by the minimum level of design definition appropriate for the application of the intended simulation technique or tool. Simulation techniques and the associated software tools are usually applied to a design once the design is largely defined and the process involves the concurrent input of many players from various disciplines rather than the few designers at the concept phase.

Late in the design process simulation is used to quantify and/or assess the performance of the design against a set of specific design requirements. Should problems be revealed by a specific simulation, it is then likely to be far too late and extremely costly to rethink the design to resolve them. Instead, rather than

considering the origins of the problems encountered (i.e. the root causes), it seems to be common practice to manually modify the system, for example, eliminating the non-compliances or, at least, diminishing their consequences. Thus, the modifications to the design are generally of a local nature (i.e. limited to the area of the design where the weakness is identified or, better, where the downstream consequences of a problem manifest themselves) and the resulting design certainly could be seen as a sub-optimal compromise since the root causes of the problems may well remain unaddressed. Inevitably, as a result of this concentration on mitigating the effects of a given set of problems rather than on resolving their original causes, compromise or remedial solutions are adopted.

The above consideration reinforces the contention that simulation should start in preliminary design not only to save on costs, but also to enable the early identification, addressing and resolving of the fundamental design problems. This would then reduce the risk compromising performance in later stages of the design process. With this perspective, the research has considered whether and to what level this early integration of simulation in preliminary ship design is possible in the case of simulating personnel movement evolutions.

### **2.2.1 Preliminary Ship Design issues**

To further clarify the complexity involved in the ship design process and to draw attention to the crucial importance of its preliminary stages, it is necessary to give a brief description of how the process of design progressively develops from its initiation. Usually, the ship design process is initiated by the owner's needs [Andrews, 1986] and, at the outset, the task takes the form of an exchange of ideas between the designer and the 'requirements owner' [Andrews 2003b and 2010].

This discussion is informed by a range of suitable design options identified and assessed through design explorations, investigations and finally trade-off studies. Once the requirement is clarified and commitment to proceed obtained, then an increasingly more detailed working up of the design by a substantial and expanding multidisciplinary team can proceed to lead on the production of a design definition capable of being manufactured, constructed and assembled. Later phases of design require comprehensive design management procedures and are constrained by the early design decisions made on overall configuration and other important aspects which are best identified as associated with the term ‘style’ [Brown and Andrews, 1980]. The term “Style”, in this context, refers to a wide range of issues not all of which are amenable to numerical investigation, particularly in the early stages of design. Examples of stylistic choices were given by Andrews [1984] and include survivability standards, the overall architecture of propulsive machinery and margin policy. A broad range of issues can be incorporated in the definition of the “style” of the design, including: personnel movement, ease of outfitting, functional flexibility (adaptability) and location, layout and sizing of critical spaces such as the Bridge, Ship Control Centre, Operations Room, machinery spaces, accommodation and the main access routes linking them.

In large scale design the more detailed design phases are undertaken and managed by disaggregating the whole design into discrete subsets and assigning their refinement to different teams of specialist engineers and designers while the naval architectural team ensures the maintenance of the balanced ship design intent. A balanced ship design refers to a naval architecturally balanced design where the design is balanced in the traditional aspects of primary ship performance, both in its technical and configurational features.

Considering the pervasive use of computer aided design tools and the growing necessity of exchanging large volumes of information to improve concurrent engineering between teams from different disciplines, the use in the final design for production phase of computer based integrated product data environments (IPDEs) and integrated product models (IPMs) is intensifying [Johansson, 2002]. The downstream design work is characterised by numerous design decisions which have limited impact on the totality of the integrated model features and thus the overall design concept emerges as essentially determined in its main characteristics from preliminary design. This reinforces the importance of the decisions taken during the initial stages of design and emphasizes that they constrain the final solution. This also justifies the research presented here, specifically focusing on the integration of simulation techniques into initial design. However, this does mean that initial design needs to be more descriptive than traditionally has been the case. The advantages of such an early integration are discussed as well as ways to effectively take into account those aspects, such as ship-scale ergonomics and operability, which previously have been difficult to address in the initial phase.

### **2.2.2 Human Factors integration**

One condition seen to be indispensable in ensuring that human factors procedures, methods and techniques are integrated with the normal ship design activities (including those of preliminary design stages) is that ship design models are treated as integrated product models, therefore including HF features such as the characteristics of the embarked personnel and operational procedures, as fundamental components of the model (this is discussed further in Section 3.6).

Procedural integration of HF analysis has been supported and encouraged by various disciplines and, particularly relevant to this research, by proponents of Concurrent Engineering [DoD, 1999]. Human Systems Integration (HSI) has been described as the technical process of integrating elements such as manning levels, personnel characteristics, Human Factors Engineering (HFE), Health and Safety (H&S) hazards, habitability and survivability factors within a system with the goal to ensure safe and effective operability and maintainability (supportability) of the equipment and the system itself [Kevin et al., 2006].

For the successful implementation of a HSI programme from the conceptual design through construction and operation, a comprehensive approach to integrate the various domains needs to be developed with particular consideration to the HFE element. Andrews [2006] states Human Factors Engineering to be the integration of Human Factors with the design process; HFE has been formally defined as “an interdisciplinary science concerned with influencing the design of manned systems, equipments and operational environments so as to promote safe, efficient and reliable total system performance” [MoD, 1990].

In literature, there are several similar descriptions of the main objectives of a successful HF programme but, in explicitly considering HF in ship design, Calhoun and Stevens [2003] summarize them as being:-

- “ a) improved human performance,
- b) reduced training and training costs,
- c) improved use of manpower by reduced need for special skills and aptitude,
- d) reduced loss of time and cost by reducing human errors, and
- e) improved comfort and acceptance by users.”

An early UK Ministry of Defence guidance document for effective Human Factors Integration Plan (HFIP) development [MoD, 1992] identified the main domains to be addressed when the above listed objectives are considered in ship design; the guidance has been updated in the documents [MoD, 2005] produced by the Human Factors Integration Defence Technology Centre (HFI DTC) where the main domains are summarised in six categories:-

1. manpower and personnel requirements: considering numbers and skills requirements of the personnel including the common HF issues associated with job and task design but also the ship specific issue of complement validation, which is crucial to ship design, operation and through life cost, where the complement represents the dominant factor;
2. training: addressing man-machine and man-ship interaction aspects across the domains of command, operation and maintenance through facilities onboard and ashore. This category also includes ship-related components, such as aeronautical (e.g. helicopters and airplanes) and underwater (e.g. submersible vehicles and UAV);
3. environmental engineering: encompassing the internal (artificial) and external (extreme) ship environment, with particular emphasis on the need to isolate the human environment from exposure to risks and hazards and to limit the consequences of accidents, particularly those related to onboard systems and ordnance;
4. health hazards and system safety: considering normal hazards at sea and on-board safety issues. It also includes the scrutiny of accident statistics and possible protective equipment as well as the design of escape routes and provision of life saving appliances;

5. accommodation and habitability: regards the identification of any opportunity to raise living standards and of any condition, inherent in the operation of the ship or related to its facilities, which could affect the long term performance of personnel;
6. human engineering: covers traditional small scale ergonomics issues, such as design criteria for controls and displays, vehicle and work place concerns over workstation design, as well as human traffic flow.

This research focuses on the integration and impact on the ship design process in its preliminary stages of a cross section of the six main domains described above, specifically addressing issues such as crew operations, human engineering and internal configuration and layout.

### **2.2.3 Micro and Macro ergonomics**

There is an important aspect to be emphasized when considering ergonomics which is particularly relevant when this discipline's principles are applied to large scale design projects, such as ships. In fact, Human Factors play a significant role and have a great impact on the design of complex systems and could be considered at two complementary levels: that of micro-ergonomics and of macro-ergonomics [Kavwowski, 2001].

Traditional HSI analysis and professional practice have been concentrating on what could be called micro-ergonomics: the study of human reliability in relation to the surrounding physical environment, technology and design aspects of workplace, training, information and work organisation [Ho and Duffy, 2000]. Micro-ergonomics applied to ship design, for example, aims to achieve effective person-machine interfaces and efficient maintenance and repair operations.



Principles underpinning this ergonomics approach to the assessment and design of products, equipment and systems, focus primarily on improving the human-machine interface level, the human body's responses to physical and physiological loads and the related methods of measurement, types of investigation and analysis techniques [Hancock and Szalma, 2003 and Dix et al., 2004].

While such local improvements are important, increasingly, there is pressure upon ergonomists to achieve whole system improvement. In addition, one could consider issues related to what could be defined as “large-scale micro-ergonomics”: a discipline addressing the interactions between entities where each interaction is individually analysed at a micro-ergonomic scale. The focus of this approach to ergonomics is on the design and evaluation of interfaces between humans on the one side and physical environments, structures, layout and arrangement of spaces, workplaces and other specific equipments on the other. This, in marine design, is referred to as the criteria applied to the design and construction of all hardware within a ship or maritime structure that the human crew members come into contact with, in any manner for operation, habitability and maintenance purposes [ASTM, 2007].

Conversely, there is the analysis of macro-ergonomics issues: the study of organisational and management aspects of the design of socio-technical systems, including their organizational structures, policies and processes [Rouse and Boff, 2005, Klaus and Zink, 2006]. Also addressed as organizational ergonomics, macro-ergonomics is concerned with a systems-based approach to the optimisation of the overall system performance [Carayon and Smith, 2000]. In the case of naval systems, relevant topics include designing the watch-keeping organisation and

assessing the trade-off between automation and overall manning onboard vessels.

Another aspect which differentiates these two levels of addressing into Human System Integration (HSI) is that while micro-ergonomic issues can, and generally are, addressed late in detailed design phases, large-scale micro-ergonomic and macro-ergonomic matters necessarily require a much earlier consideration. It is the contention of this research that the latter aspects should be not only addressed in early design stages, but also integrated early on in the design process such that it influences the major early design choices. Thus, the important aspect of personnel movement on board ships has been addressed given it represents a major factor influencing the operability and usability of the whole ship and as it is strongly related to the overall physical arrangements or architecture of the vessel [Andrews, 2005]. These large-scale personnel movement issues are closely interconnected with the traditional macro-ergonomic design aspects. It is suggested that these aspects could only be properly taken into account in initial design, when the layout and overall ship configuration are still being evolved.

The characteristics against which the approach propounded in this research has been measured were identified by Andrews [2003a] in regard to the consideration of a philosophy of ship design, including simulation, and seen as the features required of any preliminary ship design process in providing:-

- “ 1. believable solutions - meaning ones that are both technically balanced and sufficiently descriptive;
2. coherent solutions - meaning that they assist the dialogue with the customer, which should be more than a focus on numerical measures of performance and cost and should include visual representation;

3. open methods - in that they are responsive to the issues that matter to the customer or are capable of being elucidated from the customer or from user teams;
4. revelatory - so likely design drivers are identified early in the design process to aid effective design exploration and risk reduction; and
5. creative - in that options are not closed down by the design method and tool adopted but rather exploration of alternatives is fostered.”

All the issues raised in this section are pertinent to the approach of integrating personnel movement simulation into preliminary ship design. The proposed approach is, in principle, also applicable to the wider approach of integrating simulation into preliminary ship design and into the initial design of other complex environments (e.g. buildings, transport terminals and shopping centres).

## 2.3 Simulation and design

Given the scope of the research, it is necessary to clarify and distinguish what actually constitutes a simulation, to outline the specific types of simulations that have been used and are to be referred to in Chapter 3, and to justify the need to use such techniques in engineering design.

Simulation could be defined as the act of representing the behaviour or characteristics of a selected physical or abstract system through the use of another system [Hartmann, 1996; Humphreys, 2004]. Simulation is not the mere imitation of the behaviour of some situations or processes, obtained by means of something suitably analogous or designed for the purpose; rather, it is the reconstruction, based on few simple principles, of the relevant processes governing the subject of the simulation. Attempting to predict aspects of the behaviour of some system, complex

entity or process, generally entails creating a simplified description, synthesised in a mathematically approximated model and representing its key characteristics. Simulation techniques are based on the use of models to recreate a situation, often repeatedly, so that the likelihood of various outcomes could be more accurately estimated. This can be done by physically modelling, by writing a special-purpose computer program or using a more general simulation package applied to a particular kind of simulation.

Simulation is used in a wide variety of scientific disciplines, ranging from astrophysics and geology to nano-scale mechanics and bioengineering. It is also applied to the modelling of socio-economic, business and natural systems (including human and human-in-the-loop systems) in order to gain insights into their functioning and behaviour. In general, simulation is required when it is impossible or extremely costly to produce and test a prototype. Other areas include simulation for performance optimization, safety testing, medicine, training and education<sup>4</sup>.

Simulations based on the reproduction or representation of a potential situation could be also used to predict the eventual effects of alternative conditions and courses of action. This is the manner in which computer based simulation has been used in the current investigation. The key issues for this kind of simulation include the acquisition of valid source information and accurate data about the investigation's subject, the selection of key characteristics to be considered and behaviours to be analysed, the use of simplifications, approximations and assumptions within the simulation structure and, last but not least, the fidelity and validity of the simulation outcomes. These aspects are commented in Chapter 5,

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<sup>4</sup> A comprehensive set of examples can be found at [www.en.wikipedia.org/wiki/Simulation](http://www.en.wikipedia.org/wiki/Simulation).

specifically in relation to the limits to and potential use of personnel movement simulation in early stage ship design.

Given the above issues, simulation in design has generally been used in the later phases of the design process and is usually performed not by the designer but by specialised consultants. There are two main reasons for this: firstly, simulations are usually based on accurate and detailed design descriptions only available late in the design process and, secondly, both the simulation and the associated analysis of results are usually conducted using dedicated simulation tools requiring specialist knowledge and specific training. The current research questions this practice, both from a philosophical viewpoint and in its procedural implications. It is considered preferable to undertake such simulation into the early stages of design and also allow the designer, rather than an offline specialist, to swiftly assess the consequences of their decisions and, for them preferably, to evaluate the downstream implications of the simulation output for the subsequent design.

## **2.4 From CAD to CAGPSD**

Any account of how design thinking and design practice has evolved over the last forty years or so must acknowledge the all-pervasive impact of computers. The general standardization of operating systems, software products and practices, data exchange formats and general purpose CAD systems is such that the practice of design is effectively circumscribed by the capabilities provided by computers. In tracing the development of CAD, as with design itself, it is helpful to distinguish the preliminary or conceptual design applications from those for large scale and detailed CAD. The following subsections focus on advances in ship design applications of CAD.

### 2.4.1 The evolution of CAD systems

Computer Aided Design (CAD) systems have considerably evolved over the past few decades, along with the progress of computing and graphics power. Earlier CAD systems were simple bi-dimensional solutions mainly used for drawing. These still represented a big step forward over drawing boards in terms of ability to save, edit and reuse drawings. Initial three-dimensional solutions were based on ‘wireframe models’ and ‘surface modelling’ (i.e. very simple representations of a design), but later developments, achieved realistic 3D capabilities (i.e. representing the real object as a solid model). Mathematically, the definition of these models, involves the use of series of complex equations and data points.

At a high level, a CAD system could be imagined as composed of the back-end mathematical engine with the front-end providing a graphical rendering service and graphic user interface. Rendering was not a strong point of the earlier CAD programs, however, over the past decade, life-like rendering and real-time physics-based simulation (e.g. mechanical interaction between components: rotation, motion, etc.) have become a reality and are available from desktop computer systems (i.e. systems with relatively limited computational capacity and data processing power). If the quality of CAD systems’ analysis tools, user interfaces and rendering engines has considerably improved in recent times, the underlying mathematical description of the model has not changed dramatically. As a consequence, the use of these systems in design has remained mainly focused around detailed engineering design.

As highlighted by Andrews [2006], texts on CAD have concluded that synthesis, while being vital to initial design, is less amenable to computerization than analysis

[Rooney and Steadman, 1987; Taylor, 1992; Cugini and Wozny, 2000 and Chakrabarti, 2010]. Undoubtedly some of the difficulties associated with automated synthesis remain, such as the generation of spatial layouts in architecture which is largely restricted to two-dimensional modelling. Due to the limitations of CAD systems to address *ab initio* design they have been seen as much more appropriate when applied to redesign, to design of modifications and to an incremental approach in providing a design concept, which powerful analytical tools can then investigate. However, this does have the consequence that the exploration of alternative and innovative arrangements is not readily facilitated. Thus the designer is constrained to adopting solutions which CAD systems have been designed to provide. Furthermore, the limitations of the analytical tools associated with given CAD systems become increasingly significant, thus restricting the scope for innovative investigations.

An example of the way in which the initial design phase could be too readily constrained by the use of standard CAD tools is the case of made-to-order design developed using ‘intelligent CAD systems’. Made-to-order, often abbreviated as MTO and sometimes referred to as build-to-order (BTO), is a manufacturing approach in which products are designed and built only after a confirmed customer’s order for products is received (i.e. when demand actually occurs). MTO allow leveraging uncertainty about the demand for a product, hence is the most appropriate approach used for highly customised and/or low-volume products [Che et al., 2006]. “Intelligent CAD systems” refers to CAD systems which, by operating autonomously or semi-autonomously in uncertain data environments (i.e. with limited information), require minimum supervision and interaction with a human operator to perform functions, such as self-organisation

of computational tasks and adaptation to the environment, on the evolving design and for the user providing commands and instructions [Balic, 2006].

Intelligent CAD systems are widely used in MTO as they are programmed to commence design with a ‘given set of requirements’ and instructions on how to process them. This approach is unlikely to enable innovative solutions to be produced in the initial stages of a design precisely because it is limited by the logic programmed into the intelligent CAD system. This same drawback even occurs in a ‘constraint-aided conceptual design’ approach where, before schemes can be generated (i.e. synthesized), a design specification and a set of parameters (used to define the problem), instructions (directing the decision making process) and restrictions (limiting the acceptable solutions) (collectively referred to as “constraints”) are said to have to be produced [O’Sullivan, 1999].

Andrews (2006) points out that, while the growth in the computational capacity of electronic hardware has been truly remarkable, the evolution of CAD systems has not merely speeded up engineering analysis, but also enabled entirely new fields of engineering analysis to be available to the designer. Examples of this are RADAR Cross Section (RCS), noise and structural vibration or any frequency domain based analysis (i.e. using Fast Fourier Transform Functions - FFT). Yet, if anything, the impact on design has been even more profound, not just for the design downstream from initial design but also in computer aided preliminary design. This means that engineering designers need, right from inception, to change the manner in which they undertake initial design and, specifically, that they are now able to tackle several issues, including human factors aspects which previously could be at best be considered late in design [Andrews, 2006].



### 2.4.2 The use of CAD systems in Preliminary Design

The initial design of complex products using computers takes a prospective solution (using historically based algorithms) and quickly produces a balanced solution, albeit at a relatively simple level of description. It is then possible to conduct a survey of “what if” scenarios and variants to identify the eventual capability achievable, within the constraints of affordability [Hyde and Andrews, 1992]. In those circumstances, simple programming of the iterative process is both attractive and achievable, meaning that a limited design description is then advantageous. With such numerical synthesis approaches (e.g. ASSET<sup>5</sup>, PASS<sup>6</sup>) available on PCs, the effort of developing approaches to concept design became focused on means of numerically searching for solutions seen to be “optimal” from a cost-effective perspective [Lavis and Forstell, 1999], within the constraint of the limited description using automated tools and techniques, such as multi-criteria optimization, artificial neural networks, Monte Carlo simulations, fuzzy logic, decision analysis and genetic algorithms [Andrews, 2003a].

However, in the interest of achieving a divergent and creative approach to initial design, the limitations of such an approach need to be recognized. At the very early design stages, the confidence in the validity and accuracy of the design model is likely to be insufficient to have a high confidence of the feasibility of the model and of design produced. In addition, the validity of assigning relative weighting to the various numerical analyses could be even less certain.

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<sup>5</sup> Advanced Surface Ship Evaluation Tool (ASSET) is the premier early ship design tool used by the United States Navy, developed by the Design Tool Development Branch of the Ship Systems Design and Integration Division at Naval Surface Warfare Center [Carderock, 2000].

<sup>6</sup> Parametric Analysis of Ship Systems (PASS) is a whole-ship parametric design synthesis model that emphasizes the use of physics-based algorithms and is ideal for quick exploration of the design space or for examining the sensitivity of ship characteristics to changing requirements or subsystem choices. [Lavis and Forstell, 1999; Balasubramanian and Barlin, 2000]

The additional complexity introduced by performing optimization on the results of relatively simplistic initial sizing tools could be seen as supporting any argument that the move to an integrated and graphically based initial design approach is excessive in the concept phase. Andrews does consider this might be a criticism of excessive detail in PSD [Andrews, 1998]. Having outlined in this section some of the issues, Section 2.4.3 describes how the use of graphics in computer aided initial ship design has progressively evolved to produce the UCL DRC Design Building Block approach to initial ship design which is the basis for demonstrating the integration of personnel movement in Preliminary Ship Design.

### **2.4.3 The development of CAGPD of ships (CAGPSD)**

Advances in preliminary ship design conducted by the UCL DRC [Andrews and Pawling, 2006a] have demonstrated the advantages of the DBB approach to initial ship design and considered it to be the key to an integrated design synthesis. This has been facilitated by modern interactive computer graphics, which now enables the designer to swiftly explore a number of important design aspects not amenable to the “traditional numerical synthesis” in that they require more than just a numeric description and therefore have not been previously addressed at the earliest stages of ship design.

While the architecturally based approach to initial ship design has been propounded for over two decades [Andrews, 1981, Andrews 1986; Andrews and Dicks, 1997; Andrews 2003a] as more holistic approach, it was only in the 1990s with the very specific example of submarine concept design that computer graphics could be said to be sufficiently user friendly to make the approach a practical ship design proposition [Andrews, 1996].



taken into consideration during the initial design stages in a non-integrated manner and not by using CAGD systems. The lack of integration of such architecturally based design drivers into the “traditional numerical synthesis” (e.g. CONDES<sup>7</sup>, ASSET<sup>8</sup>) was due to a lack of appropriate tools and procedures to do so in an efficient and effective manner. The feedback obtained from personnel flow consideration and analysis to inform the designer from the very earliest synthesis and design is the specific focus of the research presented in this thesis.

A further feature of the Design Building Block approach that was justified and outlined in some detail for the UCL prototype system [Andrews and Dicks, 1997], is that of the “Functional” breakdown which has been fully incorporated in the SURFCON element of PARAMARINE [Bole and Forrest, 2005]. This feature considers the design and the ship description to be broken down hierarchically in terms of functions comprising “Float”, “Move”, “Fight” and “Infrastructure” categories. Developing a 3D vessel layout, while maintaining a function-based approach, entails allocating the functional definitions to physical spaces in the ship and enables the designer to explore more innovative ideas during the initial investigation. Given the prime importance of main access routes in estimating personnel performance and movement throughout the ship, an additional sub-function (namely “Access”) was highlighted and managed within the main functional group “Float” [Andrews and Dicks, 1997].

The 1997 UCL SURFCON prototype also introduced the concept of a Master Building Block to denote how the overall aggregated attributes of all Design Building Blocks were brought together to provide the numerical description of the

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<sup>7</sup> Concept Design (CONDES) is a UK MOD concept design suite and preliminary design tool to aid decision making.

<sup>8</sup> See note 5 at page 30.

resultant ship design which could then be analysed to determine the design's performance against the traditional naval architectural aspects. By providing the Design Building Block capability of SURFCON, as an adjunct to the PARAMARINE suite, the auditing of the Master Building Block can be directly undertaken through the various naval architectural analysis tools within PARAMARINE.

The general procedure adopted in producing a new ship design study has the following steps [Andrews and Pawling, 2003]:-

- “ 1. A broad outline statement of need for the ship is identified (a broad set of characteristics and, implied, constraints) and a design style proposed;
2. A few very broad Design Building Blocks containing geometric and technical attributes are selected from a library or specially created;
3. Design Building Blocks are then located as required within a configurational space and a tentative hull wrapped around the space;
4. Overall weight and space balance obtained to a sensible level (say, initially 2%) and specific performance checks (e.g. stability, resistance and powering) on the tentative ship;
5. The configuration is manipulated until the designer is satisfied;
6. Decomposition of the building blocks to greater levels of detail is undertaken as required while the overall ship balance and performance are assessed and maintained to an appropriate level.”

The incorporation of SURFCON within PARAMARINE gives access to a wide range of analytical tools beyond the basic performance issues at item 4 above.

These can then be used once the concept design is largely complete to ensure the viability of the SURFCON description.

The available tools allow the following examinations:-

1. Stability calculations against several criteria (including damage stability);
2. Resistance and Powering analysis using most well established methods and methodical series;
3. Seakeeping analysis for typical wave spectra;
4. Longitudinal strength analysis;
5. Above water vulnerability;
6. Dynamic analysis (manoeuvring);
7. Radar cross section analysis.

Given this broad procedure, the interaction with personnel flow simulation tools can be performed either at the third or fifth of the six steps above and, importantly, as part of achieving the naval architectural balance of the design. The choice depends on how much the judgements, being taken to achieve the design balance, are considered by the designer to be usefully informed by the outcome of the personnel movement simulation.

The basis of the functional specification for SURFCON, as a module within the PARAMARINE ship design software, has been spelt out in the SURFCON descriptive paper [Andrews and Pawling, 2003] with the software tools facilitates the creation of a balanced design description on which personnel movement simulations can be undertaken.

## 2.5 The use of simulation in ship design

Before outlining the progress in the integration of simulation with the DBB approach to preliminary ship design, it is appropriate to review the rationale behind the use of simulation techniques and Simulation Based Design (SBD) in ship design.

Andrews [2006] identified an early example of ‘Simulation in marine design and operation’ to be the Lloyd’s Register paper of that title [Clark et al., 1986] where a simulation was defined as being ‘an experiment using a computer model’ [Gagn’e, 1976]. Andrews also stated that, while the application of simulation techniques in directly evolving an initial design, was hard to discern, the use of computer based engineering analysis of the operational aspects of a ship could now be seen as a precursor of and a step towards, Simulation Based Design (SBD).

Andrews [2006] also considered how a study initiated in the early 90’s by the US Department of Defence (DoD) Advanced Research Projects Agency (ARPA) and entitled Simulation Based Design, spelt out methodological issues for naval ship design practice and identified further developments required [Boudreaux, 1995]. That study’s concluding observations were seen to be still quite pertinent; particularly the call for physics based simulations, the demand for large scale object oriented databases and the need for synthetic environments to be intuitive. Boudreaux concluded that the introduction of SBD was a revolution in the process of design and considered that the greatest challenge to its implementation would be ‘people and organizational change’.

Additional endorsement to the use of virtual design environments in conjunction with the use of simulation was expressed by Tibbitts et al. in a scene setting paper

on US naval ship design [Tibbitts et al., 1993]. They considered ‘SBD techniques could provide the designer the tools needed to rapidly assess the total ship impact of changes’ through the powerful and ambitious concept of a ‘virtual prototype’. This approach associated a ‘smart product model’, used in conjunction with simulation tools, would lead to the ‘future ship design process’.

This proposed combination, however, brings to question whether the front end exploratory and creative phase of the design process will inevitably be restricted by the pressure to bring the product virtual model to the level of definition necessary to carry out comprehensive and plausible simulations. Limitations on the crucial exploratory phase of the design cycle need to be watched and this is why the present research marries computer aided preliminary graphically centred ship design with simulation, rather than forcing the ship design definition into a highly defined integrated product model. Although the latter would apparently be more amenable to SBD delaying until a IPM definition was available would mean that simulation derived inputs to initial design (including a preliminary layout exploration) would not be achieved.

There has been several specific applications of simulation to downstream ship design [Kozlowski et al., 1994; Byrne and Evans, 1994; Edinberg et al., 1996; Galea et al., 2003a; López et al., 2005 and Keane et al., 2007]. Other independently developed investigations into these concepts led to the consolidation of the various applications envisaged by the initial proponents. For example, the Maritime Research Institute Netherlands (MARIN) [Dallinga et al. 2004] and CETENA [Zini et al. 2003] have used simulation techniques to more readily address the specifics of ship operability, particularly with regard to the seakeeping behaviour



of ships and its effect on crew performance. Recent examples of simulation based design in ship design and construction, such as those reviewed by Andrews [2006], have largely confirmed the theory which modern simulation is based upon and further developed the approach to SBD and the related tools. Although all these developments could be regarded as further enhancements of the 1986 LR view of the use of simulation in design, in none of these cases is the approach applied to the initial stages of design.

### **2.5.1 Escape/HF simulation in maritime applications**

Traditionally, human factors in ship design have either been ignored, considered as an afterthought or incorporated through a set of prescriptive rules. For example, human factors aspects have been associated with evacuation and these issues have been incorporated into ship design through the specification of a set of prescriptive rules known as Safety of Life At Sea (SOLAS) [IMO, 1999a]. These rules have usually been framed and amended in the aftermath of a major disaster at sea (from Titanic to the more recent Herald of Free Enterprise, Estonia, Scandinavian Star) and address such aspects as the provision of emergency lighting, signage, number of life boats, number of exits within compartments, travel distance, dead end corridors. The underlying assumption is that if the rules are followed, it will be possible to muster and abandon the vessel safely in the specified period of time.

However, the IMO have begun to introduce in its regulations more sophisticated evacuation analysis to be used in ship design. For example, the SOLAS High Speed Craft Code [IMO, 1999b] introduced the concept of performing critical path analysis of the evacuation arrangements and required Ro-Ro passenger ships

built after the 1<sup>st</sup> of July 1999 to have an early design stage evacuation analysis performed. In addition, today, more sophisticated types of evacuation analysis are possible through the use of powerful computer simulation software programs [Vassalos et al., 2000; Galea et al., 2002; Miyazaki et al., 2004].

### **2.5.2 Simulation Software: maritimeEXODUS**

As described in Section 2.7.2, there are a number of commercially available personnel movement simulation software programs. Given the aim of the research presented in this thesis and the associated EPSRC project [Galea and Andrews, 2004], the simulation tool used in the research is EXODUS as it is that provided by the EPSRC project partner.

EXODUS is a software suite developed by the Fire Safety Engineering Group (FSEG) at the University of Greenwich to simulate the evacuation of large numbers of people within a variety of complex and heavily populated enclosures (ranging from buildings to aircraft). MaritimeEXODUS is the commercially released version of the software specific for ships and off-shore installations<sup>9</sup>. This software product goes beyond the traditional personnel movement simulation based examination of layout and safety features, allowing designers, certification authorities and operators to incorporate variable human performance and environmental factors, assessment and simulation into a variety of scenarios.

The EXODUS software takes into consideration people-people, people-fire and people-structure interactions and comprises five core interacting sub-models accounting for Passenger Movement, Passenger Behaviour, Toxicity and Hazards<sup>10</sup> [Galea et al., 2002]. The software describing these sub-models is rule-based

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<sup>9</sup> More information is being updated on the FSEG website <http://fseg.gre.ac.uk/exodus>

<sup>10</sup> The Hazards sub-model takes into account the effects of heat, smoke and toxic gases.

and adaptive: the progressive motion and behaviour of each individual agent (i.e. simulated person) is determined by a set of heuristics rules. These rules are either based on experimental data (thus stochastic in nature) or on algorithms with a built-in random component; consequently, if a simulation is repeated without any changes in its initial parameters, a different set of results is likely to be generated and therefore the simulation is run many times to get statistically significant and reliable output.

The sub-models operate on agents and cells: agents are software automata representing virtual personnel; while cells are geometric entities used to discretise the simulation environment i.e. the region of space defined by the geometry of the enclosure (these concepts are explained in more detail in Section 2.7.2 and in Appendix A). The geometry can be specified by automatically importing a DXF file produced by a CAD package or manually by using the interactive tools provided within the maritimeEXODUS interface. In addition to the representation of the layout structure itself, the evacuation system can also be explicitly represented within the digital model of the ship with, for example, mustering and abandonment systems, which could also include the more detailed modelling of individual system components (e.g. Life Saving Appliances).

MaritimeEXODUS has a number of features, peculiar to sea based environments, such as ship motions impact on people and the ability to include the impact of static heel and trim on passenger and crew performance [Galea et al., 2002]. Thus, through a research contract with the UK Ministry of Defence, the capabilities of maritimeEXODUS have been extended to include the possibility to represent the performance of both naval personnel and civilians in onboard operations using

typical naval fixtures and fittings [Boxall et al., 2005]. This allows the software to better simulate key aspects of naval vessels not typically found on board civilian ships and thus produce more realistic results. Additional and important functionalities continue to be developed by the FSEG, such as those identified in the joint EPSRC project with UCL.

Another feature of the software, relevant to the scope of the research presented here, is the ability to assign passengers and crew members a list of tasks to perform [Gwynne et al., 2003]. For example, as part of an emergency evacuation scenario it may be necessary to assign passengers with an itinerary of tasks that must be completed prior to proceeding to the assembly station, such as visiting a pre-defined location to collect lifejackets. A non-emergency application may involve assessing general access of personnel to a critical heavily manned space, such as an aircraft carrier hangar. This feature is very useful as it enables the user to specify any number of complex and varied types of tasks for the simulated personnel to undertake.

In recognition of the improved ability of evacuation modelling tools, such as maritimeEXODUS, the IMO introduced a new set of guidelines for the adoption of sophisticated evacuation modelling techniques. The IMO also recommends their use in two Circulars: the ‘Interim Guidelines for a Simplified Evacuation Analysis of High-Speed Passenger Craft’ (IMO/MSC Circ.1001) [IMO, 2001] and the ‘Interim Guidelines for Evacuation Analysis for New and Existing Passenger Ships’ (IMO/MSC Circ.1033) [IMO, 2002]. These guidelines define two benchmark scenarios, “day” and “night” along with two variants, which must be simulated as part of the certification process. While arbitrarily defined,

they establish a baseline performance for the vessel with its crew thus allowing comparison with both the set target time and alternative designs.

Despite these developments, beyond the research described here crew/passenger human factors analysis remains un-integrated into ship design and the process is still commonly considered as an afterthought, usually for the purposes of verifying that the vessel meets the required standard once the vessel has been designed and, in many cases, already built.

## **2.6 Integration of CAGPSD and personnel simulation**

The UCL Design Building Block approach makes it possible to ensure, from the very commencement of the design process, that sufficient priority is given to those aspects, which are spatially and configurationally driven. Significant among these aspects in the design of both naval and commercial vessels are the features relevant to personnel and cargo movement. The movement of personnel through the ship and the achievement of an ergonomically and operationally efficient arrangement are considered to be key factors in the objective of integrating the crew into a ship design. Despite their relevance and the possibility of including them in early design iterations, these aspects are generally taken into account after other issues have been addressed (i.e. powering, stability, strength and seakeeping) and at a stage when the broad form of the layout has been already finalized [Andrews et al., 2007].

Personnel movement simulation software, in general, requires detailed design information in order to run and to output meaningful results. This has led to tools that were intended to be used late in the design process. Moreover, at a late stage any subsequent modification of the design will be constrained by the

layout and the rest of the hull characteristics already defined in detail. Thus it is likely to prove disruptive and costly in resource expenditure to make anything but remedial, constrained changes leading to significant operational inefficiencies. One of the main objectives of the research is to investigate how to overcome this by bringing the simulation analysis to the forefront of the design process.

Integrating personnel movement simulation into CAGPSD will also reflect that ship specifications have evolved with time, increasingly include performance related measures. Evolutions involving a relevant proportion of the crew such as storing, replenishment at sea, damage control, efficient watch changing in states of high readiness, security against terrorist attack at sea and in harbour, efficient policing operations from the ship and undertaking humanitarian tasks, all require an effective ship configuration and this is reinforced by moves towards “lean manning” [Hansard, 2005]. In addition, many features requiring to be incorporated in the eventual design, such as adaptability, maintainability and sustainability, are strongly influenced by the vessel’s configuration.

All these considerations cannot be adequately treated by the usual ship synthesis, which is of a numerical and gross form nature and unsuited to giving sufficient attention, in initial design, to the spatial and configurational aspects. The research presented here addresses this through investigating possible solutions to the integration of simulation into early stages design, taking the personnel movement simulation as the case study to demonstrate this approach.

The primary impediments to including human factors and more specifically personnel movement simulation in early ship design are seen to be twofold. Firstly, a General Arrangement (GA) is required to provide the layout for the

evacuation/human factors software to run. However, by the time that the GA has been sufficiently developed it is normally too late for the results of the simulation to substantially influence the ship layout or the overall ship characteristics. To avoid this, the research addressed human factors issues early in the design cycle, as the layout and main ship characteristics are being developed. Furthermore, this proposed approach should then be part of the decision making process directly influencing the selection of major hull dimensions and overall configuration. This requires the simulation tool to be interfaced with the ship configuration as enabled by the SURFCON software. Secondly, while it is relatively straightforward to identify improvements in ship performance caused by configurational changes, it is less clear how ship configuration changes might lead to improvements in human performance. For these reasons, a human performance metric (HPM) was devised to assess crew/passenger performance.

The initial development of the HPM [Andrews et al., 2007] and its usage in the EPSRC project showed the usefulness of this metric which is outlined in Chapter 3; further developments on how the HPM might be more intimately incorporated into initial ship design are discussed in Chapter 6.

A set of scenarios were required in order to provide a means of testing. Both UoG and UCL contributed to the discussion required to establish the list of scenarios, which have been defined by and discussed with the project's industrial partner (the UK Ministry of Defence - then known as Sea Systems Group, under the MoD Chief Naval Architect). These scenarios were selected in order to provide a broad set of conditions and operations with intrinsic interest for RN ship designs.

The complete list of the selected scenarios that were examined in this research is shown in Table 2.6.1. Although this represents a sub-set of the scenarios to which this approach could have been applied, it was seen as representative of the ship evolutions that would need to be considered and analysed in future ship designs, once the proposed approach had been fully implemented.

	Initial status			Scenario name	Final Status			Time (d)	Heel Angle
	Ship Readiness State	SWIC (b)	Watch (c)		Ship Readiness State	SWIC (b)	Watch (c)		
1	State 2 <sup>(a)</sup>	Y	$\alpha \beta$	State 1 prep.	State 1 <sup>(a)</sup>	Z	$\alpha \beta \gamma \delta$	D	0/20°
2	State 1 <sup>(a)</sup>	Z	$\alpha \beta \gamma \delta$	Blanket Search	State 1 <sup>(a)</sup>	Z	$\alpha \beta \gamma \delta$	D	0/20°
3	State 3 <sup>(a)</sup>	X	$\alpha$	Family Day - A	Emergency Stations	Z	$\alpha$	D	0
4	Emergency Stations	Z	$\alpha$	Family Day - B	Evacuation	Z	//	D	0
5	State 3 <sup>(a)</sup>	X	$\alpha$	IMO - A	Emergency Stations	Z	$\alpha$	D/N	0
6	Emergency Stations	Z	$\alpha$	IMO - B	Evacuation	Z	//	D/N	0
<sup>(a)</sup> State 1 → Action Stations, State 2 → Defence Watches, State 3 → Navigation Cruising. <sup>(b)</sup> SWIC → Ship Watertight Integrity Condition <sup>(c)</sup> $\alpha$ → 1 <sup>st</sup> of port, $\beta$ → 1 <sup>st</sup> of starboard, $\gamma$ → 2 <sup>nd</sup> of port, $\delta$ → 2 <sup>nd</sup> of starboard, // → no one: abandoned ship. <sup>(d)</sup> D → Day time, N → Night time.									

Table 2.6.1 - Target evaluation scenarios to be simulated: description and setup table.

The definition of each scenario is based on few simple rules and takes into account a minimal set of factors like number of crew, roles and ranks, crew duties and crew start point and target locations, information normally contained in the Watch and Station Bill (W&SB - see Appendix D).

The aim in using the proposed approach is to achieve improved personnel performance for a series of vessel variants, for example minimizing the time for a damage control party to assemble and then reach the scene of an incident or reducing the number and extent of congestion areas. The overall vessel design could then be selected from a combination of individual results from each of the scenarios, with each scenario being assigned a weighting dependent on the vessel's type and mission. The additional feedback on the design and the designer's



awareness of the downstream consequences of his/her decisions are essential for the purpose of identifying improved vessel configurations. The rationale behind this is that further analysis could better inform decisions and lead to improvements to the vessel's layout from a HF stance, which could then be promptly examined for the improvements' effects on other critical aspects of the ship's performance.

The objectives of the EPSRC project included establishing essential data transfer requirements so maritimeEXODUS' human performance simulation capability can be integrated with the design environment addressing ship configuration, which is provided by SURFCON. This required transferring the details necessary to conduct personnel movement simulation from maritimeEXODUS to the PARAMARINE-SURFCON ship model and the evaluation of the extent to which the two systems should be integrated. The final outcome of the project was delivered to the industrial partner and the EPSRC in the final report [Galea et al., 2007] and summarised in the joint IJME paper [Andrews and Pawling, 2008] (reproduced at Appendix G.1 with written discussion).

The research aimed to show a capability for integrating personnel movement simulation with computer aided preliminary and graphical ship design. This was motivated by the desire to integrate personnel related issues in initial ship design (i.e. once the first tentative ship architecture has been defined/produced) to give the designer the ability to design the super-system comprising the ship and its crew (i.e. crew numbers and skills) from early in the design evolution. The research presented in this thesis could therefore be seen as a contribution to a more holistic approach to initial design synthesis for large-scale complex design, as is described in Chapter 5. This approach is highly dependent on software capabilities both

with regards to personnel movement simulation and preliminary ship design as presented in the Section 2.7 .

## **2.7 Software survey**

The software review, surveyed information about engineering software programs dedicated to ship design and personnel movement simulation in order to produce a general overview of the best technical solutions adopted by the industry and currently available on the market.

The totality of computational models and software tools used in ship design and in simulation based design was considered too general and it was felt impossible to establish absolute evaluation criteria matching all the possible requirements of the various problems with which all possible tools might address. A software tool, in fact, could be highly specialised and ideal for some applications but not so well suited for other, and, on the other hand, another software tool can be more flexible and generally applicable, but less rigorous than another.

Given the extent of existing computational models and software tools available, the primary focus of this survey was on the specific features of the most widely used commercial-off-the-shelf (COTS) software packages and to qualitatively establish their “fitness to purpose” in terms of advantages offered, innovative solutions adopted and possible limitations.

This review informed the approach to the design of the software tools developed as part of the research. The main findings are summarised in Sub-Sections 2.7.1 and 2.7.2, while all relevant details are provided Appendix A.

### 2.7.1 Ship design software

The ship design software tool selected for the research project was PARAMARINE. Expertise and knowledge in its use lies within the UCL DRC team and the wide range of functions and the unique characteristics offered by this software make it particularly suited for preliminary ship design and thus it was highly appropriate for the research.

The feature that distinguishes the DBB approach to PSD is its graphical basis in combination with the numeric and analytical preliminary ship design ability. Thanks to the PARAMARINE-SURFCON tool, balanced ship design solutions have been produced based on a physical description of component Design Building Blocks which reflect customer needs and user requirements in the broadest sense, i.e. not limited to the traditional naval architecture features [Pawling, 2007].

These aspects can be better appreciated by comparison with other current state of the art Computer Aided Ship Design (CASD) tools. The most widely used software programs dedicated to ship design are, for example, Tribon, AutoShip, NAPA, IntelliShip and CATIA their main characteristics are outlined in more detail in Appendix A (A.1, page 224).

In general, CASD tools either provide the naval architecture analysis (hence more oriented to preliminary ship design) or a detailed description of the ship and of its components (more oriented to production). Given this split, these tools are respectively driven by the necessity to evolve the design from the initial stages and by the endeavour to support the shipbuilding demand for a detailed model to inform the manufacturing process. Examples and brief descriptions of a representative selection of the most common tools are included in Appendix A.

As already mentioned in Section 2.1, within PARAMARINE-SURFCON the overall balanced ship characteristics are held in the Master Building Block, which constitutes the ship description. This description could reflect the full range of customer and user requirements, including through life costing, health and safety issues, environmental issues, supportability, sustainability, reliability, adaptability and, importantly, all the human factors issues. Using the DBB approach the designer could model the emergent ship design solution to include and reflect all these requirements. Important for the research topic, is the ease and flexibility with which the Design Building Blocks can be reconfigured, throughout the preliminary design phases, facilitates new options being introduced, explored and assessed to exploit their possible advantages for efficient personnel movement.

The graphically centred design approach should also enable a smooth transition from the preliminary design definition to the detailed design undertaken using Integrated Product Models (IPM). Most IPMs are part of the Integrated Product Data Environment (IPDE) capability of design offices and advanced shipyards. Software vendors are implementing such capabilities in the standard releases of their products [Keane et al., 2007]. The ability of the graphical based concept tool to interface with IPMs has been demonstrated by GRC Ltd. with the portability of SURFCON models to AVEVA's TRIBON [Bole and Forrest, 2005] as part of the earlier UCL DRC led design for production project [Andrews et al., 2005].

### **2.7.2 Personnel movement simulation (PMS) software**

The marine industry, when compared with other industries, could be characterized as a synthesis of many technologies from various disciplines. As a consequence, the ship design process typically involves the use of a large number of disparate

tools to evaluate a variety of characteristics (e.g. structural, stability, seakeeping), performance metrics (e.g. speed, endurance, payload) and project phases (e.g. building, operational, maintenance) in order to enable the design to satisfy the emergent customer's requirements. It could be argued that there should be a single software package capable of addressing all the diverse aspects of design, but, at present, such a solution does not appear to be available on the market and designers are generally obliged to combine the use of several specialised software systems and/or use services provided by specialist consultancy firms.

Use of consultancies for specific analyses is particularly true for the simulation domain, since the software tools required to perform computer based simulations are generally quite complex, need very significant data processing capacity and high computing speed in addition to an in-depth user background knowledge and expertise. Given that the power of computers continues to increase rapidly according to Moore's law [Moore, 1965 and Kanellos, 2005], one could foresee such demanding computer applications being eventually executable on personal computers rather than, as is the case today, on multi-processor clusters<sup>11</sup>. Likewise, the steady progress in enhancing graphical user interfaces and the constantly reducing trade-off between information to be processed and time required to complete the analysis, are considered likely to make these applications easily understood and, consequently, become suitable for performing simulations and analysis in a timeframe acceptable to preliminary ship design practice.

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<sup>11</sup> This scenario has been analysed in detail as part of the Computational Research and Engineering Acquisition Tools and Environments (CREATE) program. CREATE is a USA Department of Defence, High Performance Computing Modernization Program (DoD-HPC Lorton, VA, USA) that plans to develop and deploy computational engineering tool sets for acquisition program engineers in order to exploit the exponential growth in supercomputer power [Post et al., 2008].

Computer aided design and computer aided engineering form the basis of modern simulation-based-design (SBD), in which both performance and production simulations are the primary means of evaluating designs. The ship product model [Whitfield et al., 2003] could be seen as the basics for the simulation environment, by containing geometrical, material and topological data, while the algorithms and the related analysis tools are fundamental elements to determine particular performances measures. These models, environments and associated tools vary considerably in their refinement and scope and the main characteristics of a range of commercially available personnel movement simulation software tools have been identified and summarised in Appendix A.

Simulation software programs could be regarded either as highly targeted to the specific application they were designed to address and, consequently, limited to that particular use, or as very broad in nature and of general applicability. In addition, according to their core simulation models, personnel simulation tools, in particular, could be categorised as described in Figure 2.7.1.

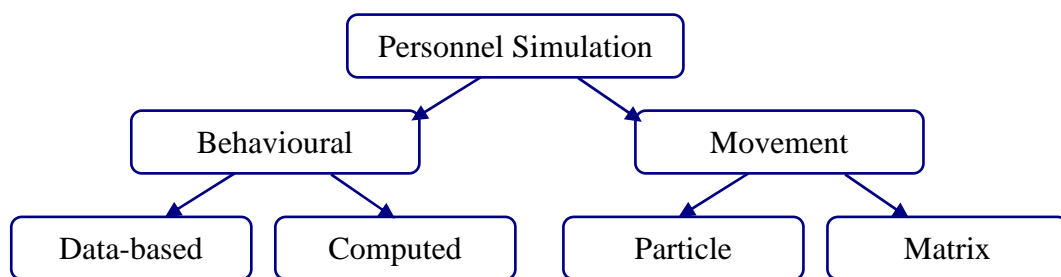


Figure 2.7.1 - General classification of personnel simulation software tools [Poulin and Yglesias, 1993].

Given their empirical nature, behavioural models cannot include the dynamics of groups in their simulations and analysis; instead, crowd dynamics emerge as a result of the contingent convergence of the individual behaviour of multiple agents. This convergence of behaviours is contingent on several factors including the

number of agents simulated in the crowd and the how the random values determining some of their decisions were generated. Assuming this is true for all data-based models, then some of the most relevant computed models (e.g. MPSM [Teknomo, 2006], CNL [Antonini et al., 2006], BMPF [Seyfried et al., 2008]) are flexible enough to incorporate certain aspects of this very important component of a simulation, through the use of appropriate algorithms [Ishaque, 2006].

Of the movement based models there are two main types: the particle systems and the matrix-based systems (Figure 2.7.1). Particle models are generally based on the analogy between crowd movement and fluid or particle motions (including interactions) and consequently use the principles of the physics of hydraulic flow. Coupling fluid dynamic and “self-driven” particle models with discrete event simulation techniques, these systems have been extensively used to help design personnel evacuation strategies. However, some studies [Still, 2000 and Pan et al., 2005] have revealed that the fluid or particle analogies of crowds are questionable as they consistently contradict some observed crowd behaviours, such as herding behaviour, multi-directional flow and uneven crowd density distribution.

Such particle modelling systems are suitable to provide a very broad idea of the possible use of space when considering the behaviour of large numbers of homogeneous agents in specific circumstances (e.g. when all the agents have the same objective). The matrix-based systems, on the other hand, take into consideration multiple dimensions of a simulation using a high number of variables, parameters and equations. Thus, these systems are also suitable for simulating a smaller population of agents dealing with more complex environments and scenarios. Matrix-based systems are among the most effective tools for simulating

operations and personnel movement in complex scenarios as they can be programmed to accommodate virtually any user requirement while, on the other hand, they suffer from difficulties in simulating cross flow and concourses [Still, 2000]. Such systems are based on the discretisation of the floor area into cells and then use cells to represent free floor areas, obstacles, areas occupied by individuals and groups of people or regions with other attributes (e.g. fire, smoke). The underlying assumption is that the virtual agents (simulated people) transit from cell to cell based on predefined occupancy rules. These rules determine the individual agents' decision making process and, because of the size of the cells, their mutual distance and the associated constraints, this could also lead to an inaccurate representation of movement in the modelled environment.

A more recently developed concept, that of 'emergent systems', promises to overcome the shortfalls of all these approaches and to build on their advantages. The underlying principle is that the interactions among simple parts can simulate complex phenomena [Johnson, 2001; Prem et al., 2005]. However, these principles and subsequent systems were not designed and developed for crowd behavioural analysis, but as general investigatory tools for the study of large scale interactive systems and, specifically, for Artificial Intelligence (AI) applications. As a consequence, currently available (early prototypes) emergent systems, typically, oversimplify the behavioural representation of individuals using a limited number of parameters and decision rules. Nevertheless, the emergent concept has potential to deliver very realistic simulations when judged against empirical evidence.

In considering the most widely used simulation software packages, particular attention was given to: the flexibility each system provided (i.e. the possibility of



being programmed and tailored to specific user needs); the available options for external compatibility (focusing on the problem of data exchange and integration with other applications); and to the philosophy, principles and assumptions on which the simulation algorithms are based (specifically concentrating on group behaviour and the capability to model the interaction between specific agents).

### **2.7.3 Software survey conclusions**

With the ever-increasing pace of technological development and computing power, software products (including ship design and simulation tools) are constantly undergoing improvements and are thus prey to rapid technical obsolescence. There is a clear tendency for modern systems to move towards a more centralised approach, where a single digital model (an IPM) contains all the information for the design [Munoz and Forrest, 2002 and Hage et al., 2006]. In this context, specialised codes for analysis and assessment of specific features of the design could either be provided by internal or external modules. In the first case integration is achieved with the use of a common interface while, in the latter, the seamless communication and interaction between the modules is assured by standardised protocols, procedures and data formats.

This increasingly extensive use of centralised object-oriented systems and relational databases (i.e. integrated models) provides the ideal ground for concurrent engineering principles to be addressed. Standards, common rules and open source codes constitute additional opportunities for collaborative efforts in design but especially in the development of new techniques, applications and tools. The level of detail is increased at earlier stages in the design process, thus increasing complexity while, correspondingly, advanced analysis and assessment tools provide increased confidence in the design. If on the one hand the number

of variables considered increases progressively with the level of detail and the number of possible design decisions increases then many associated processes increasingly need to be supported by automated procedures. This makes it possible to speed up each iteration and to progress more quickly in enduring the design, which could then ensure that decisions are made more quickly. In addition, a better informed start to the design process should lead to reduced downstream effort, since the amount of re-work and consequent re-iterations required ought to be considerably reduced.

Despite these tendencies and all their advantages, simulation based design is not yet perceived as an integral part of the design process, due to various factors, including the inherent complexity of the tools and the associated issue of data and information management. While advanced data management systems facilitate better control over the data flow, throughout the entire design process, information to ensure configuration control of the design and to track changes and revisions has to date proved to be difficult to manage [Casarosa, 2002].

Despite the promising research and development projects currently being pursued by academia and industry, there is still no comprehensive architectural solution to the problem of integrating HF aspects into complex design. This also leads to the adoption and use of bespoke combinations of different tools and the main barriers to the use of these interim software solutions are the additional requirements they generally place on the designer. While the consideration of escape and evacuation simulations has already been effectively used in static and large environments, less work has been conducted on dynamic and confined settings. Furthermore, incorporating the simulation of realistic personnel movement, operations and behaviour in computational models has proved to be difficult and challenging [Pew and Mavor, 1998 and Galea, 2003b].

### **3 - Integration development**

This chapter describes the approach followed and the work done in developing the integration of personnel movement simulation with computer aided preliminary ship design. The first four sections describe the approach, the software tools and the designs used both to develop the integration and to illustrate its use and implications. Sections 3.5 to 3.8 detail how the integration was achieved from a procedural and computational perspective, Section 3.9 focuses on operational and usability aspects of the approach and the associated software tools and Section 3.10 presents some of the most relevant modifications introduced by the development of the software to interface PARAMARINE-SURFCON and maritimeEXODUS.

#### **3.1 The approach to develop the integration**

The research presented in this thesis addresses the integration of human factors engineering, specifically operability analysis and personnel movement simulation, into the preliminary ship design utilising the Design Building Block approach. It was funded by the EPSRC and UK Ministry of Defence, Sea Safety Group [Galea and Andrews, 2004] and set five main objectives to be achieved during the project's three years:-

- “1) To explore the impact on naval ship configurational design of issues associated with crew manning numbers, function and movement;
- 2) To identify key performance measures for successful crew performance in normal and extreme conditions;
- 3) To extend the ship evacuation software maritimeEXODUS to include additional non-emergency simulation capabilities;

- 4) To extend the ship design software so that it can provide a modelling environment that interactively accepts maritimeEXODUS simulation output for a range of crew evolutions;
- 5) To demonstrate an approach to ship design that integrates ship configuration design with modelling of a range of crewing issues through PARAMARINE-SURFCON.”

The impact of improved personnel movement features on a wide range of performance attributes was investigated through a set of ship studies conducted using the preliminary ship design tool, PARAMARINE-SURFCON. Each study consists of a number of design based experiments, which tested the various aspects of features introduced and, specifically, their accuracy, reliability and general applicability. The outcome of this comprehensive investigation was intended to provide guidance on simulation integration into the design process and illustrative proposals for improvements to ship layout. To achieve the objectives set for this research project and to demonstrate feasibility and validity of the integrated approach, the project was undertaken in three phases:-

- 1) the Development Phase (DevP);
- 2) the Integration Phase (IntP);
- 3) the Demonstration Phase (DemoP).

In the DevP, ship configuration was linked with crew performance and this link tested through its application to the design of an existing class of naval combatants. In the IntP, the key software components were integrated into a prototype system. An investigation into the application of these methods and related tools was then conducted on variants of the ship configuration. In the last phase, DemoP, a new

ship design was analysed using the proposed integrated approach, the developed prototype software and the analysis environment to demonstrate its validity.

During the DevP the selected ship design was modelled and extensively investigated while, in the IntP, it was used as the base-line ship design and possible improvements identified and investigated. Further analysis was undertaken using PARAMARINE-SURFCON to determine the effect of the HF improvements on ship performance. This iterative process continued for several cycles in order to identify improved layouts based on the chosen operational performance indicators. The impact on wider ship performance and the cost impact of each improvement were examined against the achieved benefits.

As part of the IntP, requirements for interfacing the two sets of tools were identified and an approach implemented in a prototype design environment using, initially, a simple SURFCON model. As this phase progressed, the nature and the scope of the tasks to be undertaken developed from those initially envisaged. This was mainly ascribable to the new possibilities opened up by this integration of simulation into preliminary ship design. A number of possible improvements to the bespoke interface software and enhancements to the maritimeEXODUS evacuation core model were identified but their implementation proved to be quite complex and more time consuming than initially foreseen. During this phase, variant designs were modelled, taking into account the lessons learned and the guidance developed from early iterations using the prototype system. The prototype software interface was developed and refined, and an extensive investigation into the options for visualising simulation results was undertaken.

In the final DemoP, a different type of ship (i.e. not linked to the baseline model) was designed from scratch. This vessel was modelled in PARAMARINE-SURFCON and, during the early stages of its design, investigated using the refined approach and the final version of the prototype design environment developed in the IntP. The final outcome consisted of demonstrating the integrated approach along with the production of illustrative guidance, based on the performed investigations, which considered how human factors features of future warships could be improved using this approach.

### **3.2 PARAMARINE-SURFCON**

Following a theoretical introduction to PARAMARINE-SURFCON, the candidate undertook two preparatory phases of familiarisation. The first phase condensed the UCL MSc Ship Design Exercise (UCL SDE), generally assigned to undergraduate students [UCL, 2001]; and consisted of the production of a complete and balanced design starting from the outline performance requirements and following a predefined set of rules and instructions. The second phase consisted of modelling the internal layout of the ship design specified by the industrial partner in the EPSRC project, namely a Type 22 Batch III frigate (described in more detail in Section 3.4). The necessary information was provided by UK Ministry of Defence Sea Technology Group (STG now DE&S SESea) in an unclassified version of the General Arrangement drawing [MoD, 2006]. In order to generate a balanced model of the design, capable of being assessed for its main performance aspects, the description of the internal layout was populated with all the necessary information. This was obviously more detailed than would be available in a new initial design, but an existing ship class was chosen because the STG Liaison

Officer (Lt. Cdr. Boxall P.) was then able to provide the ship watch and station bill (W&SB) together with appropriate operational insights.

Throughout this initial period, a comprehensive examination of the available PARAMARINE literature and user manuals was also undertaken. Particular attention was devoted to the possible exploitation of the options offered by the use of the PARAMARINE internal programming language: the Kernel Command Language (KCL). Given the lack of information on this topic, this investigation consisted of a series of trial and error experiments aimed at understanding and mastering the KCL syntax. It was clear from the onset that the best route to the integration between SURFCON and maritimeEXODUS meant exploiting all the available functionalities and the options of compatibility with other software programs. This effort proved to be very useful in the subsequent implementation of the bespoke interface software (see Section 3.7).

### **3.3 maritimeEXODUS**

maritimeEXODUS (described in Section 2.5.2) is a multifaceted software and the theory upon which is based is very complex as justified by Glen and Galea [2002]. Proficiency in the use of this software was not seen to be necessary for the ship design team, given the collaboration between the UCL and UoG research teams. However, the candidate felt it was necessary to have a general understanding of its main characteristics, present functionalities and future possible capabilities. For this reason, an examination of the user manual and of the available literature was conducted [FSEG, 2006]. In addition, in order to achieve a more comprehensive knowledge of some important details, to discuss improvement options and to liaise with the FSEG team on aspects of the work necessary

to interface maritimeEXODUS with PARAMARINE, weekly meetings were scheduled between the candidate and his counterpart at University of Greenwich.

An examination of the various input/output data and information for maritimeEXODUS was undertaken with the aim of investigating the resources necessary to create the software link between PARAMARINE-SURFCON and maritimeEXODUS. This study on external compatibility features and interconnectivity options was not limited to the analysis of the existing possibilities, but also explored new ways to simplify the information exchange and management process.

Given the intention of the research, the focus of the interface was on the limits of the conceptual models currently implemented in maritimeEXODUS. These models are based on several assumptions, numerous algorithms and a large collection of experimental data incorporated into a set of software programs, constituting a compromise between multiple trade-offs. In Simulation Based Design, the awareness of such limitations is important as they define the domain in which the software could be used with confidence, thus constraining the software's applicability. Limitations to the simulation engine will be directly reflected in the simulation output, which could significantly constrain the input delivered to the designers involved in the ship design process.

Critically assessing the core model of maritimeEXODUS and its additional functionalities and routines (such as those related to the interface software developed as part of this research) proved to be quite challenging.



### **3.4 RN Type 22 Batch III Frigate SURFCON model**

The aims of this research phase were to produce a model as similar as possible to the Type 22 Batch III Frigate design (see Appendix D) commensurate with concept level design and the needs of maritimeEXODUS. The model had to be developed in a way that was appropriate for the envisaged study and based on the information available at the time. The model, in addition, had to retain a sufficient level of flexibility to represent preliminary design stages conditions and to allow the generation of subsequent variants. As a result, the model produced, does not reflect certain aspects, such as hullform and weight distribution, as closely as it could be achieved if modelling the existing design of the ship. However, from the comparison of significant numerical characteristics (e.g. displacement, centre of gravity position, powering), the baseline model is in close agreement with the source data and, in the crucial aspects of the layout, the actual design is well defined and consistent with the existing layout of the ship. The balance in the numerical characteristics above shows less than 3% departure from the built ship.

This model represents a naval architecturally balanced description of the design, capable of being assessed for ship performance aspects other than personnel movement, including weight and space balance, resistance, powering and stability. This allows the assessment of personnel movement and its integration into the ship design process to be conducted in an integrated manner, similar to those appropriate to preliminary design. Additionally, the use of this model provides an indication of the effect of variant designs with improved personnel flow on the whole ship design.

The modelling process necessary to provide the design environment for simulation based design investigations was broken down into four stages:-

1. Preparation and information gathering - This task was undertaken with STG providing a considerable amount of data on various areas of the design including the complete General Arrangement layout for the Type 22 Batch III Frigate [BMT DSL, 1996]. Detailed information was available on the location and associated characteristics of onboard systems and related equipment items. For example, the propulsion system, the Sea Wolf missile system and the Mark 8 gun system were modelled to the level of their main components and this level was found to be essential for the simulation of complex personnel movement scenarios.
2. Hull form, superstructure and construction of a scalable model - The hull form and superstructure models consisted of an overall “envelope” encompassing all of the internal Design Building Blocks. The hullform was controlled by a “coherence model”, which ensures that all subsequent variants on the design have consistent and realistic combinations of dimensions and hull form factors. The hullform was not modelled by the candidate, but by the Post Doctorate member of the UCL DRC team on the EPSRC project (Richard Pawling) using the information gathered from the Type 22 Batch III Book of Calculations [MoD, 1989]. Due to the PARAMARINE-SURFCON architecture and to the way in which the model was generated, any later changes to the hullform were able to be implemented without disrupting the rest of the vessel’s Building Block description.
3. DDB model generation and population with data - One of the major tasks was to assemble a Design Building Block hierarchy that modelled the Type 22 Batch III arrangements to a level of detail, representative of and suitable for preliminary

ship design, as well as for the evaluation of personnel movement. The Design Building Block hierarchy was populated with numerical data and the overall design model's accuracy and balance verified against the available information [MoD, 1989; MoD, 2000]. Figure 3.4.1 shows the DBB model where functional spaces are highlighted in blue and the access spaces in green. The verification and balance process was carried out as the model was generated, by checking the layout arrangement against the source data. Numerical data was entered into the hierarchy, which included weight, accommodation spatial demand and supply, service demand and supply and services demands and supply. The addition of equipment items (EIs), such as weapons and machinery, from the UCL DRC DBB library [UCL, 2006] and the assignment of the Design Building Blocks to specific functional groups was carried out after the completion of the layout modelling in order to speed up the process.

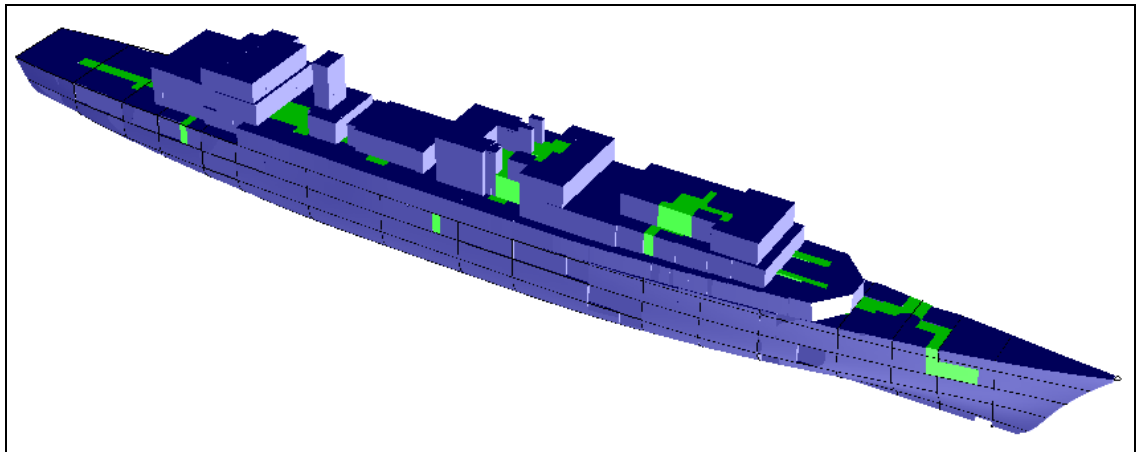


Figure 3.4.1 - Initial SURFCON model of the Type 22 Batch III Design Building Block baseline (for clarity, access spaces are highlighted in green).

The complete Design Building Block model (i.e. including the numerical description - main characteristics in Table 3.4.1) is shown in Figure 3.4.2. Blue spaces belong to the FLOAT functional group (with ACCESS routes in purple), yellow spaces belonging to the MOVE functional group of building blocks, red

blocks represent FIGHT items and the INFRASTRUCTURE functional group items are coloured in green. The design has been compared against the Type 22 Batch III design [MoD, 1989] with regard to performance aspects, such as resistance and stability and showed good agreement (i.e. displacement within 0.2% and power shaft at cruise speed within 2.8%).

	Baseline T22 BIII
Enclosed Volume, m <sup>3</sup>	19300
Deep Displacement, te	5320
Variables, te	1290
Waterline Length, m	136
Overall Length, m	146.5
Max Upper deck Beam, m	14.75
Draught, m	4.75
Shaft Power, Cruise (19 Knots), MW	6
Shaft Power, Max, MW	28950

Table 3.4.1 - Summary of principal particulars for the baseline Type 22 Batch III design.

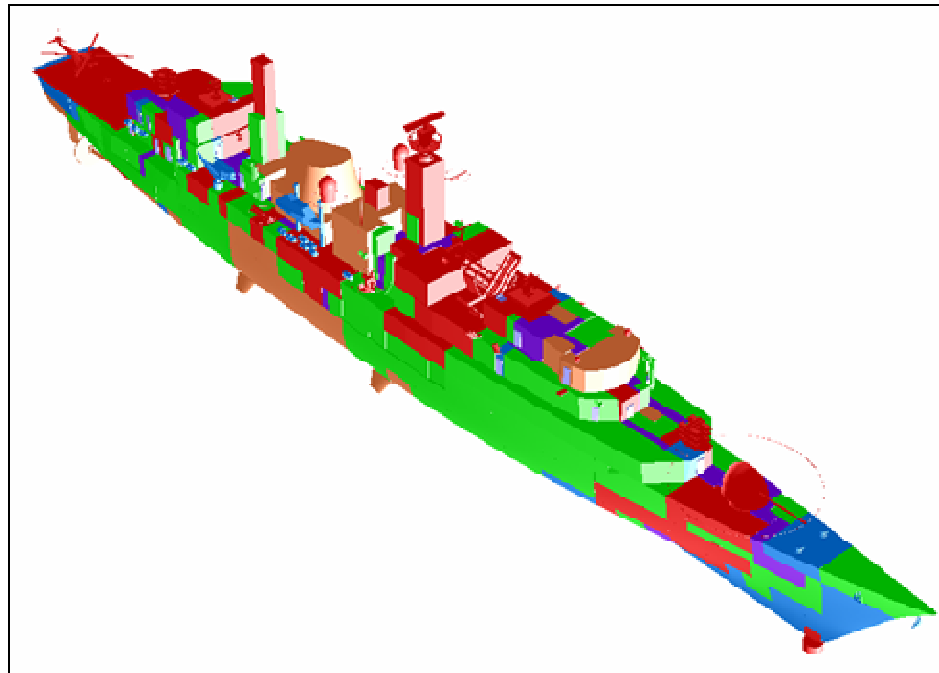


Figure 3.4.2 - Finalised SURFCON model of the Type 22 Batch III Design Building Block baseline [developed by the candidate and Dr. Pawling].

4. Insertion of HF equipment items - The spatial model, which includes the numerical properties needed for a balanced design<sup>12</sup>, was then rendered suitable for the simulation of personnel movement by adding of a number of additional items to model the required connectivity between spaces. MaritimeEXODUS, in fact, requires more than just the overall layout of the vessel to conduct simulations (see Section 3.8.3). It was necessary to include how to represent these specific features within SURFCON. Access-specific equipment items, denoted as “connectivity items”, were grouped in a library of predefined objects; this library could be seen as an object-oriented database of equipment items, not just specific to personnel movement simulation but of general applicability. The library description and the code associated to each connectivity item are included in Appendix C.

The equipment items are “define once, use many times” type of objects, implying that each instance of the object included in the model refers back to a common definition provided in the library. Consequently, the library is a stand-alone collection of visible geometries, functions and information, each directly exportable into any other design project and available for such use. The items included in this relational database ranged from watertight and non-watertight doors<sup>13</sup> to vertical ladders and inclined stairs, from hatches and emergency exits to arched openings and the hangar garage door. Each of these items was parametrically defined by a number of key factors which could be configured by the user, therefore the whole library was adaptable to fulfil the different requirements of any model (e.g. deck head height, inclined stairs angle and step numbers). Watertight doors and hatches

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<sup>12</sup> Matching of demand and supply of permanent and variable weights, consumable fluids supply and demand, electrical and propulsive power supply and demand.

<sup>13</sup> To cover all possible types, doors have been divided in sub-categories such as sliding and pivoting. Pivoting doors are further classified either as single or double doors, direction of push or pull (depending on the opening direction) and clockwise or anti-clockwise (depending of the rotation).

parameters included watertight classification index (i.e. X, Y or Z - following the RN NBCD practice [MoD, 1999]) and could also include a double opening feature.

Guidance was produced on how to use the elements of the connectivity items (CIs) library. Instructions, rules and conventions to be used were included, defining how to customise each item, how it could be included in a model, assigned to a functional group, spatially positioned and then connected to the other Design Building Blocks in the model.

It is considered that the logic underpinning the connection of each item to the rest of the design constitutes the main innovation introduced with the library of connectivity items when this is compared to that of other equipment libraries where this feature is missing (e.g. the UCL DRC library for weapons and machinery items) [UCL, 2006]. The background to this concept and its underlying logic are explained in more detail in Section 3.8 and essentially entailed linking each item in a given ship design study with the rest of the design according to a simple set of rules. If these rules are consistently followed then a network of connections can be automatically produced by a software program designed to perform this operation. Such a facility was investigated and it is considered producing such software could be the basis for a new research activity.

To assist the designer in the correct application of these rules, visual aids were implemented within the geometric description of each item included in the library. These visual aids varied with the complexity of the connectivity item they were related to and were represented, for example, by small circular indicators (shown in Figure 3.4.3 by being circled in red). These indicators are associated with each

door and visually indicate the “internal space” connected, through that door, to the rest of the model.

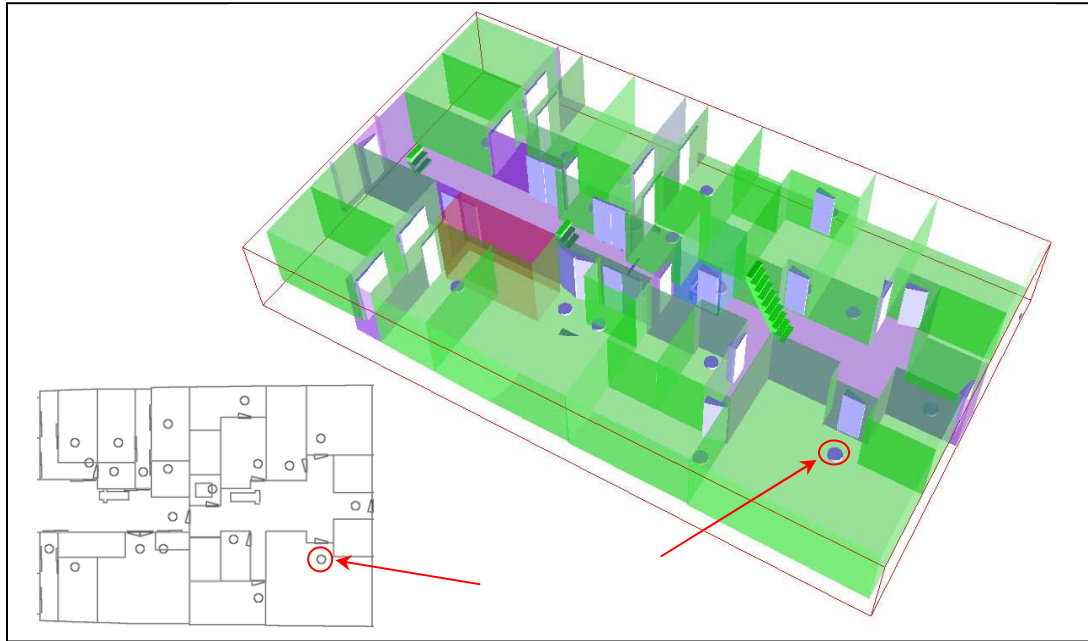


Figure 3.4.3 - Amidships area of No.2 deck of the baseline Type 22 BIII design showing ladders and doors in a 3D SURFCON view and in a 2D AutoCAD drawing generated from the SURFCON model.

Once the access routes have been modelled, the basic inputs for maritimeEXODUS were in place. However, in order to develop suitable inputs for the analysis of more complex scenarios, such as a change of watch (or those defined in Table 2.6.1) this model description has to be expanded to include new items that might not previously have been considered as part of preliminary ship design. These additional items, combined with the greater detail inherent in modelling a complete as-built design rather than at the preliminary design stage, resulted in a SURFCON model containing a significantly greater number of Design Building Blocks than would normally be expected in a preliminary ship design model. For this reason the model is referred to as the “High Resolution Baseline” model (HR Baseline model). The HR Baseline is compared in Table 3.4.2 to previous UCL DRC design studies: the Littoral Combatant Ship (LCS) Trimaran and the Dock Mothership.

The LCS was a single and detailed design while the Dock Mothership was part of a quick concept study on nine different configurations; hence despite describing a larger ship the model had a lower level of granularity in its definition.

Categories	Design		
	HR Baseline	UCL LCS Trimaran [Andrews and Pawling, 2006b]	UCL Dock Mothership [Andrews and Pawling, 2004]
Design Building Blocks (DBB)	453	343	226
Equipment Items (EI)	120	105	67
Connectivity Items (CI)	348	-	-
<b>Total</b>	<b>921</b>	<b>448</b>	<b>239</b>

Table 3.4.2 - Comparison of detail levels in PARAMARINE-SURFCON design models.

This additional complexity increased the time needed to construct the model and complicated the process of making modifications. Such modifications included the generation of several variant designs and specific local modifications necessary to conduct personnel movement simulation as required by the analysis performed using maritimeEXODUS.

During the preliminary investigation into the integration of personnel movement simulation and the DBB approach in the high resolution baseline modelling process, the question arose as to how much additional complexity was required to use the SURFCON and maritimeEXODUS tools together for effective personnel movement analysis at the early stages of design. Such added complexity of the ship model definition increased the likelihood that the analysis might not be performed early enough in the design process and hence reduce the scope for introducing significant HF related features. However, in typical initial SURFCON designs, it is not necessary to model all such connectivity features, but rather just the main “skeleton” of the access structure: main passages and vertical routes.



Although the above high level of detail was required to perform the HF analysis of the Type 22 Batch III frigate, it is important that a normal preliminary ship design level of definition be sufficient to undertake some personnel movement simulation at the early stages. Section 5.3 addresses the issue of identifying the minimum sufficient level of ship definition (i.e. SURFCON model definition or granularity level) to conduct personnel movement simulation on the modelled design and obtain meaningful results.

### **3.5 Integrating the two systems**

During the Integration Phase of the research (IntP), development and integration of the procedure and software were undertaken, together with a number of high-level procedural aspects which were identified and investigated. In addition to those general issues, the more detailed consideration of software functionality was examined in order to:-

- develop a procedure for using the two main software tools together;
- define the software integration scheme and procedure;
- develop a software tool capable of demonstrating the required integration.

This section outlines the progress achieved in developing methods, procedures and software tools necessary for using the primary simulation and ship design tools together. The proposed method is outlined, making use of an enhanced version of maritimeEXODUS and of PARAMARINE-SURFCON in conjunction with a newly developed interface tool. As stated in the aims of the project (Galea and Andrews, 2004), enhancements to both sets of software tools were undertaken, either to utilise existing capabilities for a new type of analysis or to identify and implement new capabilities. The internal modifications made to maritimeEXODUS by the UoG FSEG added several capabilities to enable transferring information and running

non-evacuation simulations. However, there remained some work to meet several issues so far identified in the investigation and these are captured in Chapter 6.

A PARAMARINE user interface was implemented which allows the rapid selection of all the information necessary for maritimeEXODUS to perform the analysis, i.e. the SURFCON definitions of objects required for personnel movement and operations simulation. Particular attention was given to the description of scenarios, procedures and operations to be used within simulations.

A bespoke prototype interface software was developed to reliably and consistently extract, translate and transfer operational and procedural information, together with the SURFCON definition of the ship, to maritimeEXODUS. This prototype software was tested for reliability and accuracy and was then used to demonstrate the concept of integrating non-evacuation personnel movement simulation in ship design. Furthermore, this software was scrutinised to improve its performance as well as to identify potential refinements to the approach on which it was based. Significantly, from a procedural integration standpoint, much of the procedure was automated, along with reducing the computational time required to undertake it.

The interface software included several modules designed to generate a flexible and interactive display of the results of the simulations. These results were provided by the EXODUS suite and include the performance measures contained in the HPM, described in Section 3.6.e , as well as additional information seen to be required to inform the design evolution. Importantly, these modules generated a graphical and interactive presentation of the results, thus allowing the designer to gain a better understanding of the performance of the design in a ready and intuitive manner. Some of these modules were fully developed as part of the

research and might need some further refinement before they can be considered for being commercially released. In fact, these modules were produced as a prototype to demonstrate the principles they are based on, to provide the basic functionality necessary to the prototype system and to produce a set of specifications for the future implementation of a fully developed system. Additional and alternative options for the interactive visualisation of results were proposed by the candidate (see Section 3.9) and could be investigated and developed as part of future research on these topics as discussed in Chapter 6.

In line with the earlier scoping of the problem, the ultimate purpose of producing this prototype interface tool was to develop the specifications for a commercially exploitable version of the interface software. This was reflected in an iterative approach to its development, which allowed the tools to be used and tested earlier in the project, even if they did not fully reflect the final software. As well as developing the new approach and associated tools, the EPSRC project aimed to provide ship design guidance that could be directly used by the MoD and its industrial suppliers. In addition, the project sought to identify any features or procedures that could be adopted as “good practice”<sup>14</sup> in design for evacuation or other personnel related operations. To achieve the goals initially set, modifications to the configuration and design issues were considered through investigating variant designs to the baseline.

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<sup>14</sup> “Good practice” means carrying out a function using only proven, recommended and approved methods. These methods and associated tools must be completely developed and audited to verify their effectiveness. Experience of their application and related results/findings must be available.

### 3.6 Procedural integration

The capability of performing personnel movement simulation during the early stages of ship design affects the manner in which design is undertaken. While refinement of the software to provide the required information in a prompt and intuitive manner is sensible, a well-conceived procedural integration of these tools is even more important. Procedural aspects were used to define the software's basic requirements and to determine the approach to be followed in any development of the prototype software.

There are five main procedure-specific issues that were considered:-

(a) Levels of Detail and Designer Input - There is a trade-off between how much detail is needed in the design, for effective simulation of operations, and the need to retain the flexibility necessary in preliminary design. A related issue is how much input is required from the designer to define all aspects necessary for the simulation. One of the most important issues to address is the identification of the minimum level of information needed to perform an accurate HF analysis at the concept design stage. Another related issue is the amount of additional effort the designer is required to spend in producing the SURFCON objects essential for the simulation. These issues were addressed throughout the investigations conducted as part of the research and used to inform the research conclusions given in Chapter 6.

(b) The Iterative Design Process - The aim of integrating personnel movement simulation into the preliminary design process revealed new options for modelling and analysis. Preliminary design is the process of investigating and exploring the design space rather than one of optimisation (such as downstream detailed design), thus the question arose as to how the integration of these options could be best used

in this design phase. Two possible approaches to achieve this integration were considered: serial and parallel. A “serial approach” consists in assessing a single design and progressively modifying it to maximise a selected effectiveness metric, while considering the consequential whole ship effects of each modification. In a “parallel approach” a number of significantly different design solutions are produced and compared in order to arrive at a final design. Benefits and limitations related to each of these two possible approaches were considered and, since they are not mutually exclusive, the conclusion of this study suggested that the opportunity to adopt one or the other, as well as a combination of the two, should be left to the individual designer. In other words particular design investigations could have their own impetus.

(c) The Wider Design Process - Integrating personnel movement simulation in preliminary ship design expands the scope of the initial design process but, as identified in point (a), additional information has to be included in the model. This was seen as an additional effort for the designer and, potentially, a disincentive to undertake such simulations early in the process. Indeed, the procedure followed by the simulated crew in each of the scenarios, the scenario definition and the watch and stations bill (W&SB) could have been fixed, or treated as another aspect of the design. In the latter case, the design could be assessed, for example, as the procedures and the W&SB are changed while the layout remains fixed. Furthermore, this could be expanded to consider total manning numbers and manning procedures onboard.

It has to be recognised that preliminary ship design is a multi-criteria process (see Section 2.2.1) and that the issues considered in this research represent only some of the criteria that can be considered as being part of the important issues driving the design evolution.

Including manning procedures planning as an additional phase in the design process is a significant procedural issue which is seen to require dedicated software interfaces and guidance and procedures on how to make effective use of it. The exchange of information between the ship designer and manning experts is the key point in this phase of the procedural integration. This could be facilitated by the method proposed in this research where the different needs of those involved in the design are integrated into a single decision making process and supported by a single computer program. This approach could also foster the development of an interactive and flexible common working environment, steer the convergence to a common and agreed solution (in line with concurrent engineering principles) [Pennell and Winner, 1989 and Brissaud and Garro, 1996] and lead to designing the ship and its personnel related aspects jointly, as is suggested by Figure 3.6.1.

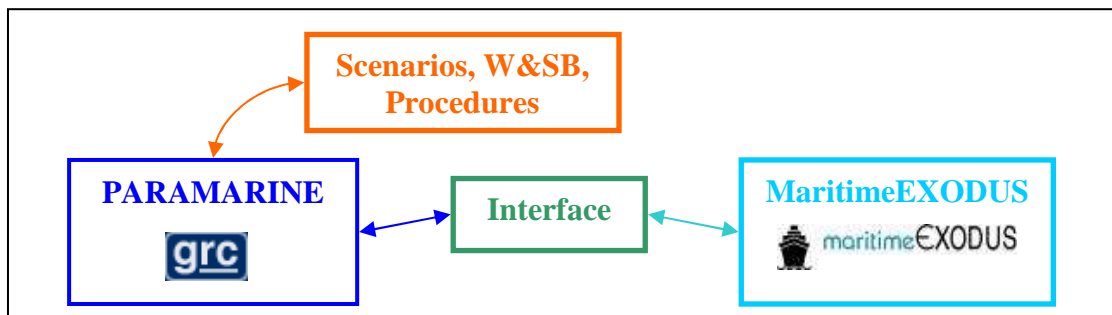


Figure 3.6.1 - Notational procedural integration scheme.

This approach, in conjunction with the relevant procedure, could eventually lead to an interactive, flexible and common working platform/environment for all the participants in a widened preliminary ship design process. As an output of the research undertaken, guidance on how this approach could be used was produced together with the instructions on how to efficiently use the necessary software tools that have been developed to enable personnel movement simulation analysis to be undertaken in the preliminary stages of ship design (see Appendix E).

(d) The Overall Procedure - The proposed procedure integrating SURFCON and maritimeEXODUS in preliminary ship design is shown in Figure 3.6.2. This procedure does not represent the overall process of iterating the ship design, in which maritimeEXODUS simulations constitute an additional performance assessment, rather it shows which operations are performed in each software package (higher boxes), including the bespoke interface software. The lower boxes in Figure 3.6.2 show the operations undertaken in each of the three tools (PARAMARINE, maritimeEXODUS and the specifically created interface).

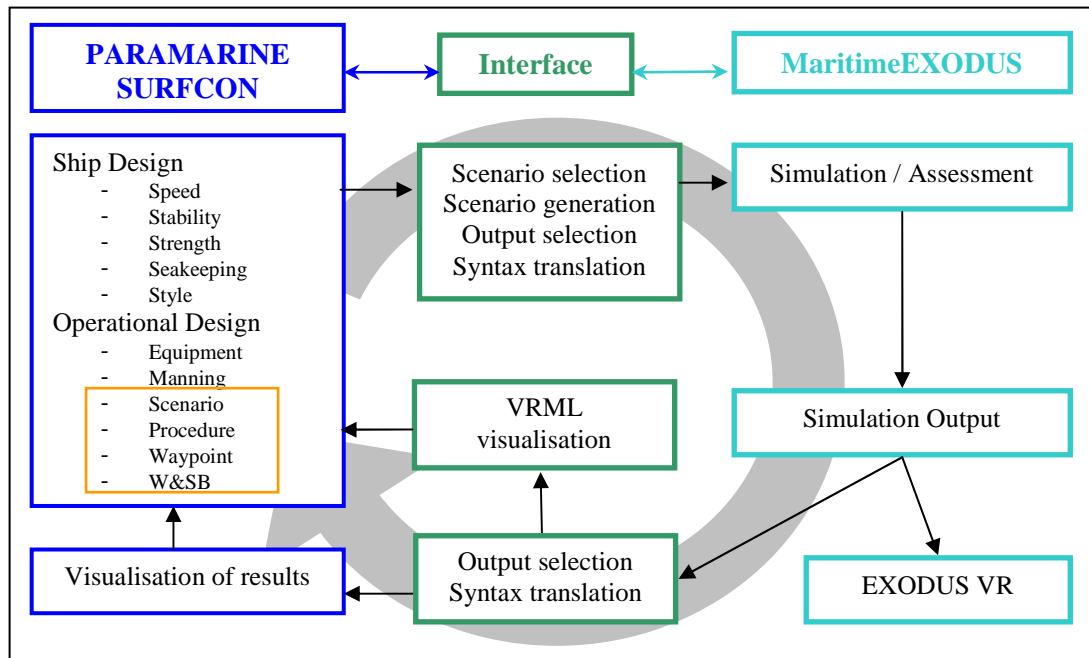


Figure 3.6.2 - Functionality diagram showing the notational integration of personnel movement simulation into preliminary ship design.

The overall concept behind the procedure illustrated in Figure 3.6.2 is that the designer has to define the vessel once and just in PARAMARINE SURFCON, as opposed to the current practice of having to redefine the vessel, either entirely or in part, within the EXODUS suite. This applies not only to the design description of the vessel, but also to the description of personnel and procedural information, as mentioned in point (c) above. In the design procedure produced, the complete definition of the design, including the operational procedures

for each evolution under examination (orange box in Figure 3.6.2), takes place within PARAMARINE-SURFCON.

Using PARAMARINE for defining the ship design model, the designer would also input additional model features to allow the investigation of specific operations undertaken by the crew. These include details of the onboard personnel and of their movement in various scenarios. Personnel information is included in the W&SB and defines the ranks of the crew, Functional Groups<sup>15</sup>, Watch Teams and on-duty roles and locations<sup>16</sup>. Simulation details consist of the setup parameters for each of the scenarios that are to be used to assess the ship design and the definition of procedures that the members of the crew are to use in each of the defined scenarios. These features were implemented as a series of tables, formatted to be easily edited, human-readable and comprehensible. These tables can be linked to the spatial model of the ship to indicate the main spaces (waypoints) used by each crew member in the scenarios. Another option included among these additional model features was that of selecting the scenarios to be simulated by maritimeEXODUS and the outputs to be recorded. These options were introduced in order to allow the designer's investigation to focus on specific aspects of the design and to save computational time.

The interface software is sufficiently robust to ensure that the model so defined is consistently translated and transferred between the two packages automatically and avoiding errors or inconsistencies. This resulted in a straightforward

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<sup>15</sup> Crew functional groups are not to be confused with the overall ship functional groups used in the DBB approach. Crew functional groups are determined by the overall manning and operational philosophy and include: First Aid, Warfare (i.e. OPS and Navigation), Warfare Support, Damage Control & Fire Fighting, Electrical, Flight, Propulsion and Machinery.

<sup>16</sup> Locations included in the W&SB include cabins, mustering locations and a placeholder for each of the readiness states.



procedure, requiring very little time to be completed<sup>17</sup>, thus opening up the options for preliminary ship design iterations, which could be based on personnel movement simulation that otherwise would have not been attempted until late in detailed design. In addition, the integration of the two tools was completely transparent to the designer who, in turn, did not need to learn how to use an additional software program (or two additional software programs if an external interface tool was required).

Ideally, the visualisation of all the simulation outputs and results would take place in PARAMARINE since the insight, which these results would provide, could be important in directly informing the ship designer. A number of possible solutions, as to how to achieve this visualisation, were developed and tested but, as it described in Section 3.8, these proved to be impractical or not feasible using the current release version of the interface software. Given the announced developments and additional functionalities to be included in future PARAMARINE releases, some of the solutions identified were considered to be possible after the EPSRC project completed in 2008 [GRC, 2007b].

At the time of writing (2010), it was possible to feed back some simulation results into PARAMARINE using a combination of two methods of presentation of the numerical data; namely tabular or graph form. To overcome this limited options, a complementary solution was developed in an external virtual reality environment (see Section 3.9). In exploring and developing these interim solutions, some of the existing visualisation and analysis tools available as part of the EXODUS suite were used.

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<sup>17</sup> The time required can vary between less than an hour and few hours depending on several factors including the computer's speed and the number of scenarios to be simulated.

(e) Output Significance – Two intimately linked procedure-specific issues were investigated, regarding the information prompting the designer and evaluating the personnel movement simulation. This information could be highly visual, intuitive and interactively displayed in the design environment or separately viewed in third party software. The choice was seen to be a significant issue, the solution of which would require further research and development of more efficient and cost-effective visualization tools and techniques were deemed to be appropriate.

The type of information necessary to evaluating the performance of a set of simulations depends on the amount of information required to be presented to the designer. Every simulation, produced by the approach demonstrated, provided large volumes of various types of data and how this is properly processed, managed and displayed is crucial to the successful implementation of the research undertaken. An excess of useful and detailed information (i.e. information overflow) would not only require longer times to be processed and examined, but also has the potential to mislead.

Given the integration of additional design aspects, such as those related to procedure planning (point (c), above), there is a dichotomy in the analysis of simulation results. The feedback received from maritimeEXODUS could in fact be used to improve the ship's spatial configuration or to develop better crew procedures. These alternative options require different information to be assessed and the choice should be the designer's. An approach produced by UoG provides insight into the performance of the onboard personnel under a number of different scenarios. This approach could enable the designer to determine the behaviours that had the largest contribution to the simulations' performance through the provision of relevant measures [Andrews et al 2007]. Such an approach would allow the designer to analyse and interpret the extensive quantity of numerical results produced by maritimeEXODUS' simulations.

### 3.6.1 The Human Performance Metrics

The approach of presenting the personnel performance data in a logic organisation of the simulations output data (i.e. the Human Performance Metrics - HPM) led to the development of a complex matrix made by sets of nested tables and named the “Human Performance Matrix” (HPMx). The HPMx can be defined as follows: a set of nested and multi-dimensional matrices populated with all output data deriving from personnel movement simulations conducted in maritime EXODUS (a representative but partial example of such a matrix is shown in Figure 3.6.3). The UoG team proposed this approach as the means to assess the results of the simulation and was developed according to the specifications generated by the candidate as described in this section. However, this approach was not fully implemented during the EPSRC project to provide a practical representation and a readily usable design tool [Gwynne et al., 2005]. The high level characteristics of the HPMx are outlined in this section while a more detailed description can be found in Appendix G.1 (Ch. 3, page 283).

Scenario	Heel Angle	Functionality Grouping																General Results					
		Warfare		Warf. Supp.		DC +FF		Eled.		Flight		Prop + Mch.		First Aid		User-specified Crew		Civilian Pop.		Scen. Coeff.	Scen. Score	Prep time	Op time
1	State 1	0	a <sub>1</sub>	a <sub>2</sub>	a <sub>3</sub>	a <sub>4</sub>	a <sub>5</sub>	a <sub>6</sub>	a <sub>7</sub>	a <sub>8</sub>	a <sub>9</sub>	a <sub>10</sub>	a <sub>11</sub>	a <sub>12</sub>	a <sub>13</sub>	a <sub>14</sub>	a <sub>15</sub>	a <sub>16</sub>	S <sub>1</sub>	V <sub>1</sub> =f(a <sub>1</sub> ,...a <sub>16</sub> )	a <sub>17</sub>	a <sub>18</sub>	a <sub>19</sub>
2	State 1	20	b <sub>1</sub>	b <sub>2</sub>	b <sub>3</sub>	b <sub>4</sub>	b <sub>5</sub>	b <sub>6</sub>	b <sub>7</sub>	b <sub>8</sub>	b <sub>9</sub>	b <sub>10</sub>	b <sub>11</sub>	b <sub>12</sub>	b <sub>13</sub>	b <sub>14</sub>	b <sub>15</sub>	b <sub>16</sub>	S <sub>2</sub>	V <sub>2</sub>	b <sub>17</sub>	b <sub>18</sub>	b <sub>19</sub>
3	Blanket Search	0	y <sub>1</sub>	y <sub>2</sub>	y <sub>3</sub>	y <sub>4</sub>	y <sub>5</sub>	y <sub>6</sub>	y <sub>7</sub>	y <sub>8</sub>	y <sub>9</sub>	y <sub>10</sub>	y <sub>11</sub>	y <sub>12</sub>	y <sub>13</sub>	y <sub>14</sub>	y <sub>15</sub>	y <sub>16</sub>	S <sub>3</sub>	V <sub>3</sub>	c <sub>17</sub>	c <sub>18</sub>	c <sub>19</sub>
4	Blanket Search	20	d <sub>1</sub>	d <sub>2</sub>	d <sub>3</sub>	d <sub>4</sub>	d <sub>5</sub>	d <sub>6</sub>	d <sub>7</sub>	d <sub>8</sub>	d <sub>9</sub>	d <sub>10</sub>	d <sub>11</sub>	d <sub>12</sub>	d <sub>13</sub>	d <sub>14</sub>	d <sub>15</sub>	d <sub>16</sub>	S <sub>4</sub>	V <sub>4</sub>	d <sub>17</sub>	d <sub>18</sub>	d <sub>19</sub>
5	Family Day	0	e <sub>1</sub>	e <sub>2</sub>	e <sub>3</sub>	e <sub>4</sub>	e <sub>5</sub>	e <sub>6</sub>	e <sub>7</sub>	e <sub>8</sub>	e <sub>9</sub>	e <sub>10</sub>	e <sub>11</sub>	e <sub>12</sub>	e <sub>13</sub>	e <sub>14</sub>	e <sub>15</sub>	e <sub>16</sub>	S <sub>5</sub>	V <sub>5</sub>	e <sub>17</sub>	e <sub>18</sub>	e <sub>19</sub>
6	IMO (Day)	0	f <sub>1</sub>	f <sub>2</sub>	f <sub>3</sub>	f <sub>4</sub>	f <sub>5</sub>	f <sub>6</sub>	f <sub>7</sub>	f <sub>8</sub>	f <sub>9</sub>	f <sub>10</sub>	f <sub>11</sub>	f <sub>12</sub>	f <sub>13</sub>	f <sub>14</sub>	f <sub>15</sub>	f <sub>16</sub>	S <sub>6</sub>	V <sub>6</sub>	f <sub>17</sub>	f <sub>18</sub>	f <sub>19</sub>
7	IMO (Night)	0	g <sub>1</sub>	g <sub>2</sub>	g <sub>3</sub>	g <sub>4</sub>	g <sub>5</sub>	g <sub>6</sub>	g <sub>7</sub>	g <sub>8</sub>	g <sub>9</sub>	g <sub>10</sub>	g <sub>11</sub>	g <sub>12</sub>	g <sub>13</sub>	g <sub>14</sub>	g <sub>15</sub>	g <sub>16</sub>	S <sub>7</sub>	V <sub>7</sub>	g <sub>17</sub>	g <sub>18</sub>	g <sub>19</sub>
Overall Performance of Functionality Groups		Overall Performance of design																Overall Performance of design					
		W=F(a <sub>1</sub> ,...g <sub>16</sub> ), V=F(a <sub>1</sub> ,...g <sub>16</sub> ), C=F(y <sub>1</sub> ,...y <sub>16</sub> ), D=F(d <sub>1</sub> ,...d <sub>16</sub> ), E=F(e <sub>1</sub> ,...e <sub>16</sub> ), F=F(f <sub>1</sub> ,...f <sub>16</sub> ), PM=F(g <sub>1</sub> ,...g <sub>16</sub> ), FA=F(a <sub>1</sub> ,...a <sub>16</sub> ), U=F(u <sub>1</sub> ,...u <sub>16</sub> ), CP=F(c <sub>1</sub> ,...c <sub>16</sub> )																					
		Y <sub>overall</sub> =F(S <sub>1</sub> ,P <sub>1</sub> ,S <sub>2</sub> ,P <sub>2</sub> )																					

Warfare Scenario	I1	I2	E3	G1	G2	G4	G5	G6	G7	P1	Scenario Score										
1	A <sub>11</sub>	s(I1)	A <sub>12</sub>	s(I2)	A <sub>13</sub>	s(E3)	A <sub>14</sub>	s(G1)	A <sub>15</sub>	s(G2)	A <sub>16</sub>	s(G4)	A <sub>17</sub>	s(G5)	A <sub>18</sub>	s(G6)	A <sub>19</sub>	s(G7)	A <sub>20</sub>	s(P1)	a <sub>1</sub>
2	A <sub>21</sub>	b(I1)	A <sub>22</sub>	b(I2)	A <sub>23</sub>	b(E3)	A <sub>24</sub>	b(G1)	A <sub>25</sub>	b(G2)	A <sub>26</sub>	b(G4)	A <sub>27</sub>	b(G5)	A <sub>28</sub>	b(G6)	A <sub>29</sub>	b(G7)	A <sub>30</sub>	b(P1)	b <sub>1</sub>
3	A <sub>31</sub>	c(I1)	A <sub>32</sub>	c(I2)	A <sub>33</sub>	c(E3)	A <sub>34</sub>	c(G1)	A <sub>35</sub>	c(G2)	A <sub>36</sub>	c(G4)	A <sub>37</sub>	c(G5)	A <sub>38</sub>	c(G6)	A <sub>39</sub>	c(G7)	A <sub>40</sub>	c(P1)	c <sub>1</sub>
4	A <sub>41</sub>	d(I1)	A <sub>42</sub>	d(I2)	A <sub>43</sub>	d(E3)	A <sub>44</sub>	d(G1)	A <sub>45</sub>	d(G2)	A <sub>46</sub>	d(G4)	A <sub>47</sub>	d(G5)	A <sub>48</sub>	d(G6)	A <sub>49</sub>	d(G7)	A <sub>50</sub>	d(P1)	d <sub>1</sub>
5	A <sub>51</sub>	e(I1)	A <sub>52</sub>	e(I2)	A <sub>53</sub>	e(E3)	A <sub>54</sub>	e(G1)	A <sub>55</sub>	e(G2)	A <sub>56</sub>	e(G4)	A <sub>57</sub>	e(G5)	A <sub>58</sub>	e(G6)	A <sub>59</sub>	e(G7)	A <sub>60</sub>	e(P1)	e <sub>1</sub>
6	A <sub>61</sub>	f(I1)	A <sub>62</sub>	f(I2)	A <sub>63</sub>	f(E3)	A <sub>64</sub>	f(G1)	A <sub>65</sub>	f(G2)	A <sub>66</sub>	f(G4)	A <sub>67</sub>	f(G5)	A <sub>68</sub>	f(G6)	A <sub>69</sub>	f(G7)	A <sub>70</sub>	f(P1)	f <sub>1</sub>
7	A <sub>71</sub>	g(I1)	A <sub>72</sub>	g(I2)	A <sub>73</sub>	g(E3)	A <sub>74</sub>	g(G1)	A <sub>75</sub>	g(G2)	A <sub>76</sub>	g(G4)	A <sub>77</sub>	g(G5)	A <sub>78</sub>	g(G6)	A <sub>79</sub>	g(G7)	A <sub>80</sub>	g(P1)	g <sub>1</sub>

A										
Scenario	I1	I2	E3	G1	G2	G4	G5	G6	G7	P1
1	0	0	0	2	2	2	2	1	2	2
2	0	0	0	2	2	2	2	1	2	2
3	0	0	0	2	2	2	2	1	2	2
4	0	0	0	2	2	2	2	1	2	2
5	0	0	0	1	2	1	2	1	1	1
6	2	2	0	1	0	0	2	1	1	0
7	2	2	0	1	0	0	2	1	1	0

Figure 3.6.3 - Nested structure of a multidimensional Human Performance Matrix [Gwynne et al., 2005].

The elements that represent the main components of a HPMx are the values described by HPM and these can be organised as being associated with the following key elements:-

- 1) Evaluation Scenarios (ES);
- 2) Functional Groups (FG);
- 3) Performance Measures (PM);
- 4) Specific Performance Measures (SPM);
- 5) Weighting Coefficients for Normalisation (WCN).

In addition to the definition of the Evaluation Scenarios (ES) as from Table 2.6.1, a range of Performance Measures (PM) must be defined. These measure various aspects of personnel performance in undertaking the tasks associated with the ES. For example, the PM for passenger ship evacuation scenarios may include the time required to complete the assembly process while for a naval vessel Normal Operations Scenarios (NOP), the total number of water tight doors (WTD) opened and closed may be relevant. The suitability of the vessel's layout would be evaluated for fitness for purpose through a specific combination of the PM resulting from the execution of the ES, processed by a computer and organised in an HPMx.

Collectively the particular combination of ES and PM that results in a meaningful measure of the performance of the crew and vessel are described as the Human Performance Metric (HPM). The coefficients associated with HPM will be specific to the type and class of vessel being investigated thus, for example, an aircraft carrier will have a different HPM setup to that of a submarine. However, the underlying concept of the HPMx will be common to all types of vessels and some HPM may be similar across different vessel types. The HPMx, was developed with the aim of allowing the systematic comparison of one layout design against

another, whether they are two variants of the same design or two completely different designs.

The HPM data contained in the HPMx was divided into seven classes. These classes refer to Specific Performance Measures (hence are named, SPM classes):-

- Class I - IMO derived criteria
- Class E - Environmental criteria
- Class G - General measures
- Class P - Procedural criteria
- Class U - Population measures
- Class M - Geometric measures
- Class C - Congestion criteria

Each sub-set of behavioural measures developed by the candidate and included in the performance matrix developed by the FSEG team at UoG is identified by an ID. The ID is composed by a letter (indicating to which of the seven classes the sub-set belongs) and a number (uniquely identifying each specific sub-set of measures). Some examples of the most significant measures included in each of these HPM classes are described below, in Table 3.6.1 .

ID	Description of parameter
I1	The number of locations and the maximum time that the IMO population density condition of four people/m <sup>2</sup> for more than 10% overall time was met
E3	The number of fatalities due to exposure to critical levels of toxic gas or smoke
G1	Time spent in preparation; i.e. those activities required prior to the commencement of purpose movement
G2	Time spent performing actions; i.e. the time spent performing pre-defined actions
G4	Time spent in transition; i.e. moving from one location to another
G5	Time to reach final state; i.e. the overall time needed to perform the complete scenario (required to complete all operations)
G6	Absolute time spent in congestion [This could be an average or the total time spent in congestion for all people on board]
G7	Absolute distances travelled as average or the total distances for all people on board
P1	The number of operations required (i.e. individual actions performed by active crew)
U2	The number of active agents in a simulated population; i.e. those involved in pre-defined actions required in order to complete the scenario under examination.
M3	Total time watertight doors (WTD) and hatches had been opened
M6	Longest time that a WTD/hatch had been open during scenario

Table 3.6.1 - Sub-set of all the behavioural measures developed by the candidate and included in the performance matrix developed by the FSEG team at UoG [Gwynne et al., 2005].

To populate the HPMx, each measure would need to be recorded during every simulation performed on any specific scenario on a per-agent basis, i.e. for each active agent in the simulated population involved in that scenario. In order to provide meaningful information on the performance of the ship and its crew during the set of specified scenarios (as outlined in Table 2.6.1), these measures ought to be presented in an aggregated manner for each design.

To construct the HPMx, all the data produced by the simulations and stored in an EXODUS database have been aggregated in a set of tables representing the crew sub-populations (the crew functional groups (FG) - see note 15, page 7). All data relevant to a specific personnel movement simulation (i.e. data from the simulation of a specific scenario) are then combined together according to certain weighted coefficients, thus the Weighting Coefficients for Normalisation (WCN) is shown in Figure 3.6.4.

These coefficients were intended to be extracted from a predefined database, which would have determined the impact of the reported behavioural measures (i.e. the importance of each measure was accessed according to the sub-population and scenario settings). However, it was not possible to develop the database of coefficients as exhaustively as desired, due to the limited resources available for this task. Instead of such a database, a set of coefficients was determined based on information available from experience and in consultation with the industrial partner. These coefficients were included in the matrix and maintained fixed during the exploration of the approach and sensitivity analysis conducted on the use of the HPMx defined by these parameters.

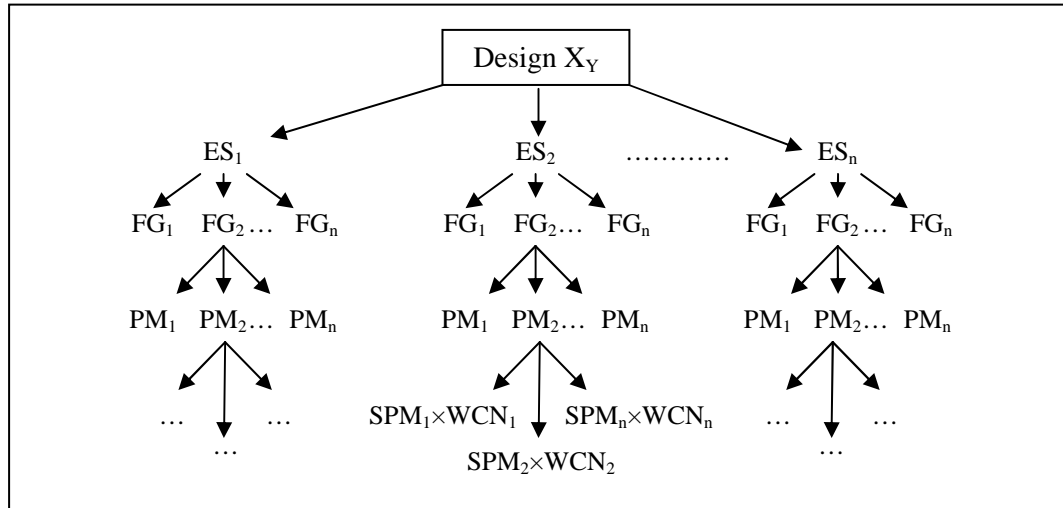


Figure 3.6.4 - Tree diagrams showing the relationships between the various components of the HPMx.

The HPMx can be used to compare the human performance capabilities of competing vessel designs (Design  $X_1$ ,  $X_2$ ,  $X_3$ , ...  $X_n$ ). As described in Section 3.6, (point b) these alternative designs may simply be different design iterations of a particular vessel (serial approach) or competing design options (parallel approach). To assess the performance of the competing designs, a set of evaluation scenarios is selected ( $ES_1$ ,  $ES_2$ , ...  $ES_n$  in Figure 3.6.4). Each ES is relevant to the intended operation of the vessel and the ones selected for the purpose of the study presented are those shown in Table 2.6.1 and the relationships between the various components of the HPMx are illustrated in Figure 3.6.4 .

The design alternatives are then crewed with the required number of personnel and the crew assigned to their Functional Groups ( $FG_1$ ,  $FG_2$  ...  $FG_n$  in Figure 3.6.4). The number and type of FG may differ between design alternatives for each ES because, the HPMx calculates and allows the comparison of the overall performance of different designs. Each Functional Group ( $FG_i$ ) has a set of Performance Measures ( $PM_1$ ,  $PM_2$ , ...  $PM_n$ ) defining the how the cumulative performance of a given FG is calculated.

If, in each of the designs under examination, an equivalent number of FG has been defined, then the HPMx allows comparing the performance between equivalent functional groups. The same applies for the complement numbers: if designs have the same complement, the HPMx allows a detailed comparison between the designs to be performed down to a level where the individual performance of each crew member in one design can be compared to that of the performance of the corresponding member in another design.

An example of HPMx with scenario and design score along with the all the associated individual scores and weights, is presented in Table 3.6.2. The overall Vessel Performance, (VP for Design  $X_1$  ( $VP_{\text{DESIGN } X_1}$ )) is the parameter that can be compared against the VP score of other designs to determine which design produced the best overall performance. The VP score is a number and is calculated as the weighted sum of the of all the evaluation scenarios scores ( $ESS_1, ESS_2, \dots ESS_n$ ) using a set of predefined scenario weighting coefficients ( $SW_1, SW_2, \dots SW_n$ ). In turn, as shown in Table 3.6.2, each ESS is calculated as the weighted sum of the scores all FG obtained in the simulation of one ES ( $A_{11}, A_{12}, \dots A_{1n}$ ) giving a set of weights ( $\alpha_{11}, \alpha_{12}, \dots \alpha_{1n}$ ) associated with each score.

Design X <sub>1</sub>										
Evaluation Scenario	Functional Groups								Scenario Score	Scenario Weight
	FG <sub>1</sub>		FG <sub>2</sub>		...		FG <sub>n</sub>			
ES <sub>1</sub>	A <sub>11</sub>	α <sub>11</sub>	A <sub>12</sub>	α <sub>12</sub>	...	...	A <sub>1n</sub>	α <sub>1n</sub>	ESS <sub>1</sub>	SW <sub>1</sub>
ES <sub>2</sub>	A <sub>21</sub>	α <sub>21</sub>	A <sub>22</sub>	α <sub>22</sub>	...	...	A <sub>2n</sub>	α <sub>2n</sub>	ESS <sub>2</sub>	SW <sub>2</sub>
...	...	...	...	...	...	...	...	...	...	...
ES <sub>n</sub>	A <sub>n1</sub>	α <sub>n1</sub>	A <sub>n2</sub>	α <sub>n2</sub>	...	-	A <sub>nn</sub>	α <sub>nn</sub>	ESS <sub>n</sub>	SW <sub>n</sub>
FG Scores	SFG <sub>1</sub>		SFG <sub>2</sub>		...		SFG <sub>n</sub>		VP <sub>DESIGN X1</sub>	

Table 3.6.2 - General HPMx structure for Design  $X_1$  showing individual weights.



The HPMx can also be used as a diagnostic tool in that its nested structure and the way in which its components are calculated allows the identification of which measures contributed to the poor performance of vessel design. In fact, the HPMx was intended to provide the designer with an indication as to the total personnel related performance of the design during the simulated scenarios, while also allowing the designer and the HF expert to view a summary of the results and of the performance of the constituent functionality groups.

The nested structure of the HPMx was intended to facilitate the analysis of the results available in the summary and explore in detail the root causes of any poorly performing scenario. Until more experience can be gained in determining how well this approach to assessing the personnel movement simulation results would meet the perceived requirements and achieve the desired functionality, this configuration can only be considered as indicative rather than definitive.

The approach developed at UoG regarding the population of the HPMx with raw data extracted from numerous simulations also allowed for the possibility of directly comparing the performance of two different ship designs against the same set of scenarios. This ought to enable the impact of any modification introduced in the design to be evaluated, if a serial approach is adopted (as described in Section 3.6). If, conversely, a parallel approach was to be used, such a comparison would allow a quantitative comparison of the effects on the overall performance (and, potentially of each of the main contributing factors) of the different solutions implemented in two competing designs.

The use of these tools and techniques was tested and refined. Considerable progress in this direction was achieved and conclusions as to how an optimum

balance between the data processed (and recorded) during the simulations and the information made available and/or presented to the designer are included in Section 5.2.5 .

### **3.7 Software integration**

In order to ensure the procedural integration outlined in Section 3.6 above was achieved, a fully functioning software link was implemented. This was a prototype and a developmental tool (i.e. not intended to be an industry usable and fully implemented product), however it provided the basic functionality allowing PARAMARINE-SURFCON and maritimeEXODUS to be used together.

The prototype interface software facilitated both the development of a practical procedure and produced a clearer indication of the required functionality for any future industry usable application to integrate personnel movement analysis into preliminary ship design. In developing the prototype, a number of issues were addressed. These ranged from the most efficient way to define the operational procedures, to a comprehensive and effective post-processing visualisation and representation of the simulation results.

The main driver behind the integration of the main integration tools was that the overall ship design iteration should take place in PARAMARINE, while the personnel movement simulation should be executed externally to PARAMARINE and as a batch process (i.e. automatic, not requiring any user supervision or intervention). This would allow the designer to focus directly on ship design aspects while retaining the inherent SURFCON flexibility necessary to modify the design.

The software procedure was developed around the existing functionalities of both maritimeEXODUS and PARAMARINE. This meant it was not necessary to wait for any desired developments to either or both main software tools to

be introduced and released. Rather additional effort would be required after this research project to identify a full range of capabilities existing in both software packages that subsequently could be adapted and used to create the required interfacing. However, several new features and significant additions and modifications were introduced by UoG to the EXODUS core model, to make it capable of dealing with non-egress simulations and the wide range of new operational scenarios considered in the EPSRC project.

The strategy followed in developing the interface software derived directly from the main aims of the research project (Galea and Andrews, 2004) and from three other factors: the findings from the software survey (Appendix A); the integration logic described in Section 3.6 (and summarised in Figure 3.6.2); and the candidate's ship design experience and software programming skills.

The main rationale behind the requirements for the interface software was that, ideally, human factors and operational analysis, conducted using personnel simulation, should seamlessly integrate into the ship design process. This would then provide the designer with the required information, presented in a convenient and intuitive manner. According to the aims of the research and to the related Integration Plan, the requirements for the bespoke interface software were seen to be:-

1. Highly automated and transparent to the designer;
2. Assembled following a modular approach;
3. Developed around PARAMARINE existing functionalities;
4. Programmed using currently available tools;
5. Able to use the minimum amount of additional information (granularity);
6. Intuitive with a user-friendly user interface;
7. Capable of allowing different types of analysis (direct and comparative);
8. Customisable, depending on the analysis conducted and on results required.

The software integration plan consisted of six distinct phases:-

1. Identification of the essential types of information to be transferred;
2. Syntax translation between SURFCON and maritimeEXODUS;
3. Design of the user interface;
4. Design of ways to visualise the simulation results;
5. Software optimisation;
6. Guidance development and specification of future requirements.

Section 3.8 describes how the above outlined requirements for the prototype software system were achieved.

### **3.8 Interface software design and development**

Software design and development can be defined as the effort undertaken to create software for computer-based systems. There are a number of approaches to designing and developing software and these can vary quite considerably, depending on the intended use. The difference between different approaches lies in scope, complexity and context. Different approaches have also been devised to meet the different environments in which software is developed and operated. In the context of this research and in consideration of the software requirements outlined in the previous section, the candidate opted for a simple approach for which ease of programming and availability of coding support were the decisive factors.

In general, software design and development can be split in two parts: the architecture and the code. The software architecture describes the general mechanics of the software system (i.e. a work plan on which to base the coding), while the code describes in detail how the software system is build and the way in which it functions (i.e. the set of instructions that will execute the work plan). For the purpose of creating the interface software and to enable the integration between PARAMARINE-SURFCON and maritimeEXODUS, the candidate chose

a modular architecture and an object-based programming language, which are outlined in this section and described in more detail in Appendix E.

### 3.8.1 The interface software development

Software development can be a very protracted process. To speed up the process of investigating the feasibility of interfacing the two substantial software suites and, at the same time, to facilitate the production of a fully functioning prototype software system, the candidate decided to approach this task using a rapid trial and error technique. Every single module of the interface software was progressively developed and intensively tested on a simple SURFCON model: the “Demonstrator” (DEM). Figure 3.8.1 shows the simplest model (DEM v1.0) used at the very beginning of this development work. This initial model consisted of two compartments joined by a single passageway with two doors connecting the spaces together, with the associated basic simulation consisting of five crew members directly moving between Room 1 and Room 2, through a narrow passageway.

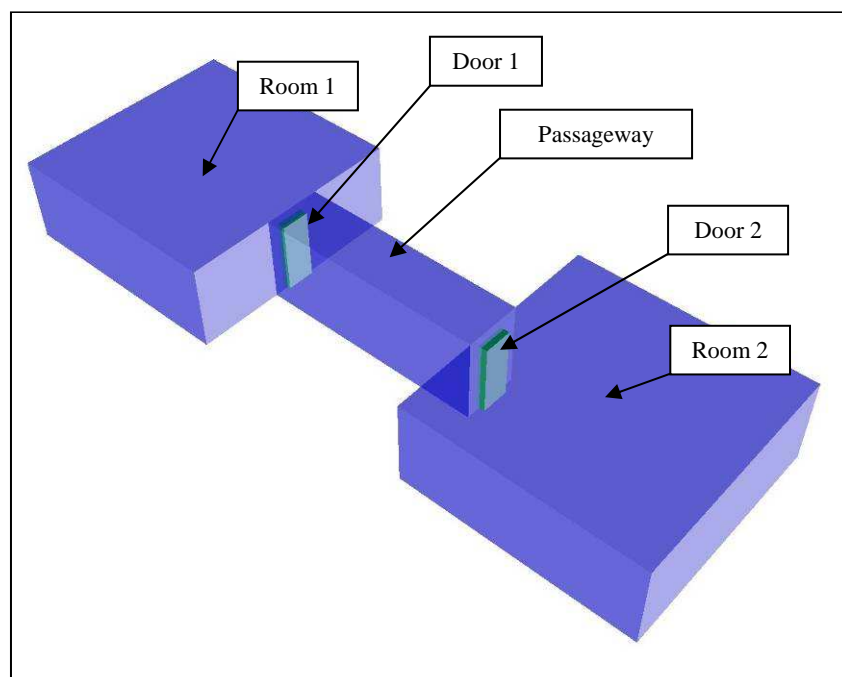


Figure 3.8.1 - The Demonstrator SURFCON model used for the interface implementation (DEM v1.0).

The bespoke interface software was developed around the Demonstrator since, despite being a very simple model, is sufficiently general in its description and complete in all its characteristics to represent a more elaborated model by using the same elements and features. This was justified by a specific investigation, conducted as part of the preliminary work, to assess the validity of the proposed approach to the development of the interface software. This investigation showed that, provided nothing else changed, the number of times a particular item (e.g. a Design Building Block or an equipment item) was used in the SURFCON model description would be proportional to the scale of the model. This also meant it would also be proportional to its file size without altering its codification complexity (i.e. the elaborateness of its computerised definition). Therefore, for example, developing the interface software code around the small DEM v1.0 or around a network of hundreds of rooms and corridors, interconnected by horizontal and vertical connectivity items, required exactly the same effort in terms of number and complexity of algorithms to generate. On the other hand, the advantage of working on such a model meant it was of a considerably smaller file size which, in turn, led to faster computational times. Calculating time, in this case, refers to the computational time (or CPU<sup>18</sup> time) required to perform all the operations required to decode (or translate) the model's digital code from its original SURFCON syntax (i.e. that of the KCL syntax) to a format compatible with the interface software. As an example of the relative difference in computational time due to the size of the model, translating DEM v1.0 required around five minutes on a standard PC, while running the Type 22 model through the initial version of the software took around four and a half hours on the

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<sup>18</sup> The central processing unit (CPU) is a component of a computer system that carries out the instructions of a computer program and is the primary element carrying out the computer's functions.

same computer. The small amount of time required to decode the Demonstrator rendered the whole software development process significantly more manageable and considerably faster, as more tests could be run in the same amount of time.

This step-by-step technique enabled a limited number of new variables to be introduced and addressed in each software design iteration. Systematically restricting the investigation field of each of these iterations also helped reduce the time needed to find solutions to problems that arose during each examination and, eventually, reduced the time to update the software with new functionalities. Using this rapid trial and error approach, as soon as all the technical challenges encountered were resolved (i.e. when the interface software was able to transfer the Demonstrator model's representation into maritimeEXODUS) meant the model definition could be progressively enriched with additional elements and features.

New software modules were progressively developed and introduced by the candidate, new algorithms were also implemented and the overall architecture of the software modified and adapted accordingly. This method allowed all the required investigations to be carried out and enabled the software to be finely tuned to take into account the additional model complexity introduced with each iteration. Given the considerable advantages offered, the same method was adopted for the development of the software modules dedicated to transferring the simulation results from maritimeEXODUS back into SURFCON. The description of the initial results is outlined in Section 3.9 .

Software runs and trials were performed on a number of modifications made to each version of the Demonstrator model. Such modifications were systematically implemented not only to the configuration and/or to the internal layout of

equipment items and associated characteristics, but also to the operational procedures to be performed by the crew. A large number of simulations need to be undertaken in order to determine whether and to what extent both the interface software and maritimeEXODUS were sensitive to the changes introduced in each of the test cases. Therefore, the flexibility and the general validity of the interface program was extensively tested and assessed. The progressive complexity of the Demonstrator was enhanced by increasing the level of definition of the spatial description of the SURFCON model, through the inclusion of more equipment items and by introducing more complex operational procedures (i.e. defining a range of scenarios with different levels of complexity). The complexity of these procedures ranges, for example, from a simple transfer of a small functional team (e.g. a damage control team) from a location to another, to more elaborated change of watch and evacuation type of scenarios.

Figure 3.8.2 shows the most complex version of the model used in the final stages of the interface software development (Demonstrator version 132.7). The numbering system of each version of the Demonstrator model was defined as follows: the first number indicated the number of new elements and features introduced in the SURFCON model and the second number (i.e. after the dot) represented the software version number. Thus a total of more than 250 versions of the Demonstrator model were produced to facilitate the production of the interface software.

Although the systematic enhancement of the software capabilities was a continuous process, from a code implementation point of view, this progression had to be divided into a number of discrete phases, each corresponding to a new software version. Each new version differed from the previous one in its core code, in the



arrangement of its algorithms and in the interactions between its modules. For example, after finalising and testing all the modifications that were introduced while developing a given version of the software, the corresponding additional modules were individually optimised and then integrated back in the main program's code. It has to be noted that these new modules, as well as the whole program, were refined in terms of logical integration and computational performance by aiming specifically at reducing to a minimum the number of operations performed and, as a consequence, minimising the computational time required to run the whole code.

DEM v132.7 (shown in Figure 3.8.2), as the final version of the Demonstrator model, includes all the features necessary to perform personnel movement simulations on a complete set of scenarios equivalent in variety and complexity to those described in Table 2.6.1., which indicated the set of personnel movement scenarios investigated in the EPSRC project. All the HF related equipment items included in the equipment-library were placed in this model (one item per class). Some of these architectural features are visible in Figure 3.8.2 (e.g. different types of doors, stairs, vertical ladders and ship equipment). This model's definition, together with the extensive simulated trials conducted using it, was assessed as being sufficiently general to consider that the integration task was achieved and that the developed interface software (in its Version 7) was of general applicability. This was demonstrated and additional further refinements to the code, which might have additional utility, were identified in the very last phase of the software development process, where Version 7 was applied to the Type 22 Batch III SURFCON model rather than just DEM v 132.7 .

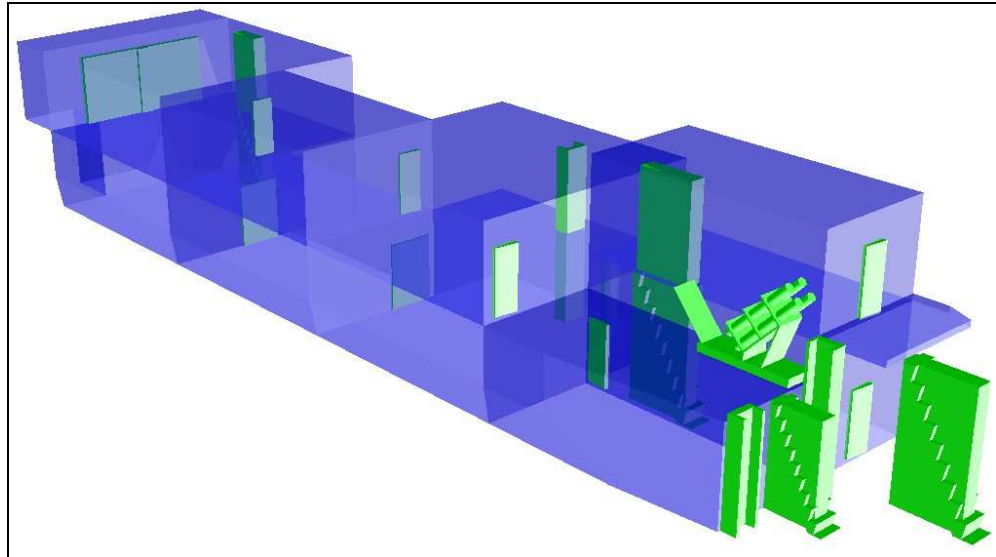


Figure 3.8.2 - The Demonstrator SURFCON model (DEM v132.7) used in the final stages of the interface software development.

Thanks to the extensive testing performed on the Demonstrator model, the application of the interface software to the Type 22 Batch III model was successfully performed at the first instance. Some minor problems were identified and, consequentially, a few adjustments and marginal improvements were then easily implemented to the software.

### 3.8.2 The interface software prototype

The final version of the interface software prototype (Version 8) included all the corrections from the application to the Type 22 Batch III model and represented a significant improvement over the previous version in a number of different respects. Firstly, it incorporated new functionalities developed during the analysis of the Type 22 baseline model. These were introduced to further enhance the existing ship modelling options and to resolve some additional minor problems, mainly ascribable to specific limitations of maritimeEXODUS. Secondly, while Version 7 consisted of a toolset, combining several MS Excel spreadsheets with numerous macro routines used in conjunction with a HTML user interface

and a JavaScript tool, Version 8 is a single program entirely developed in Visual Basic (VBA) using MS Excel as a platform for data handling and processing. Thirdly, its general applicability was successfully tested and, to date, its execution has been error free. Version 8, in fact, consistently and reliably transferred operational and procedural information together with the SURFCON definition of the ship and connectivity information to and from maritimeEXODUS in all the cases examined. Lastly, Version 8 was fully automated and optimised: it required very few interactions with the user and took an average of 30 minutes to complete running, as opposed to Version 7 where each module had to be setup and run individually and the whole process took nearly four hours to complete. Additionally, its execution is totally transparent to the designer and does not require any particular guidance to be used.

Considering the progressive advancement from the initial version up to the final version and the results achieved in using it, the systematic plan adopted for the development of the interface software proved to be successful. Version 8 of the prototype interface software met all the requirements set and constituted a significant contribution towards achieving the goals set for the EPSRC research project.

The same approach was used to develop the software modules that are used to generate the visualisation of the results (see Figure 3.8.3, Figure 3.8.4 and Figure 3.8.5). These modules were then progressively refined and finalised (as described in Appendix E) and were eventually able to display the outputs from the simulations in a clear manner and within a highly interactive environment (see Section 3.9).

The initial results showed the validity of the tools used and of methods followed in developing and using this system.

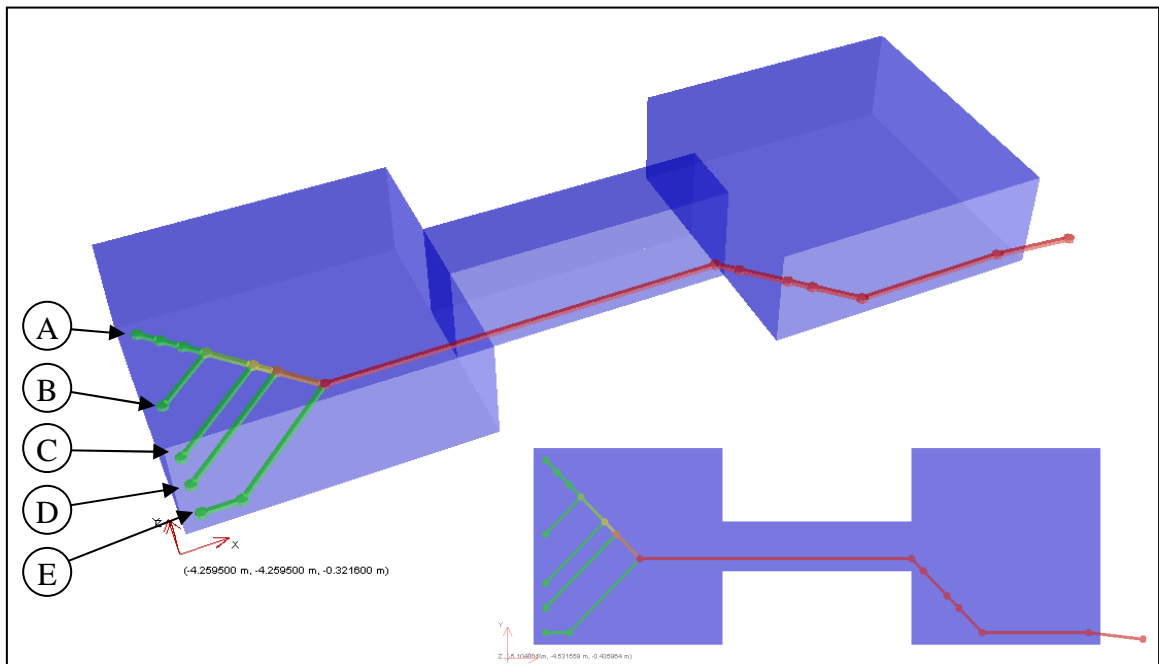


Figure 3.8.3 - Example of visualisation of results in PARAMARINE-SURFCON for the DEM v2.4 model with five different paths (A to E) partially overlapping and introduced as part of the model.

Simple simulations of personnel movement were performed during this phase using the basic geometries of the demonstrator model. At this stage the candidate developed a Visual Basic (VB) macro that processed the output of simple simulations (i.e. the .VRS file) into an input format suitable for PARAMARINE-SURFCON. In this early version of the prototype interface software, the VB macro created a KCL macro file which could be executed by SURFCON to create a visual representation of the post-processed simulation data, as shown in Figure 3.8.3. Figure 3.8.4 and Figure 3.8.5 show different visualisations of these simple simulations exploring all the options available. Further technical details on the procedures and files used are given in Appendix E.

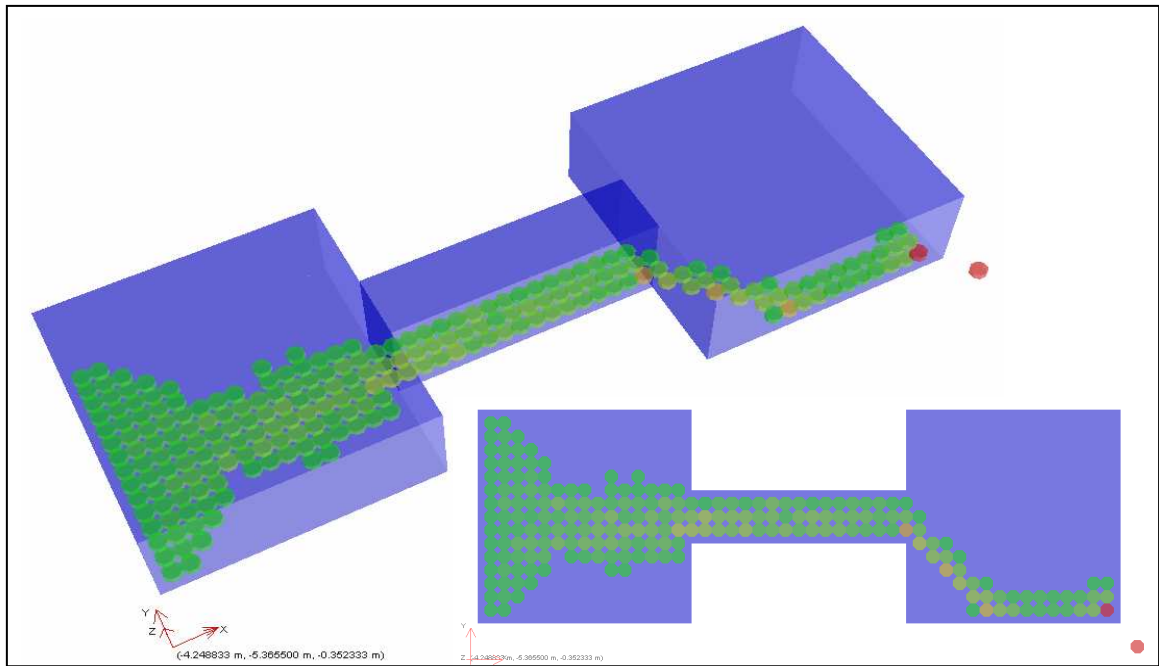


Figure 3.8.4 - SURFCON nodes used to represent a footfall density map.

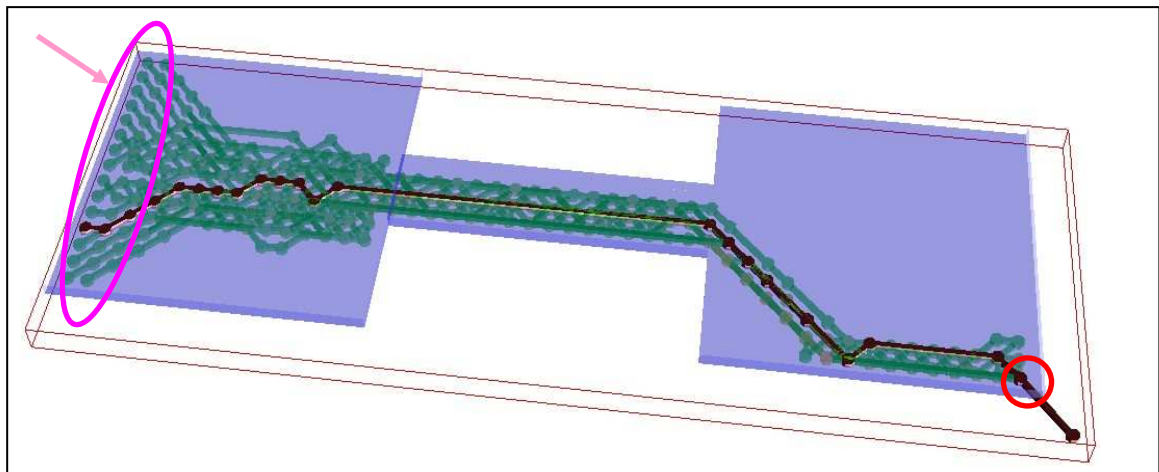


Figure 3.8.5 - Route map of a simulation of 30 individuals moving from an initial position (in the pink circle) toward the exit node (bottom-right corner) where a single path has been highlighted.

In the KCL-created footfall density maps, red nodes indicate heavily used regions. The final figure (Figure 3.8.5) shows every path taken in the simulation. It was considered that these two types of graphical display would best convey the simulation information in assessing the performance of a given design.

### 3.8.3 Identification and transfer of information

This phase of the software integration plan consisted of exploratory studies for exporting the design definition from PARAMARINE-SURFCON into maritimeEXODUS. maritimeEXODUS, however, requires more than just the overall layout of the vessel or the layout information, usually included in a SURFCON model, in order to generate its own model and effectively conduct a personnel movement simulation.

In order to allow the designer to undertake all model definition activities in a single design environment (i.e. PARAMARINE), an in-depth investigation was conducted on how to best define, introduce and represent all the required maritimeEXODUS inputs in the SURFCON model. This investigation involved the identification of the type of data that could be transferred between the two programs and how this could be achieved, in terms of file types and data formats. The main objectives of this phase of the development were to identify the essential data transfer requirements and the types of INPUT / OUTPUT information necessary to allow the assessment of both personnel and ship performance during the simulations (i.e. the production of the HPMx and an equivalent matrix for the ship).

From the investigation conducted on maritimeEXODUS, a description was produced grouping the types of data needed to achieve a model description suitable to be tested. The essential information to be included in a maritimeEXODUS model (i.e. the minimum set of data required for it to run simulations) was divided into seven classes. A summary of such information is included in Table 3.8.1 .

<b>Geometric data</b> Number and name of each deck Layout of the vessel (plan view of each deck) Boundary polygons (logical arrangement of the geometry) Location of equipment items (systems, ordnance, etc.) Location of mustering stations and Life Saving Appliances (LSAs)
<b>Connectivity data</b> Location of horizontal and vertical connections between spaces Connectivity scheme/map for accessible spaces Transit nodes types (door, ladder, stairs, hatch, etc.) Transit nodes list and properties (width, time to operate, etc.) Class of each connection (watertight/non-watertight class: X, Y or Z)
<b>Descriptive data</b> Compartment and equipment items names Database of compartment names related to their location Compartment types (cabins, corridors, engineering spaces, etc.) Subdivision in watertight compartments (vertical and horizontal) Subdivision in fire zones Initial state of equipment items (active or inactive)
<b>Personnel data</b> Initial population size and type (Rank, role on ship, etc.) Onboard locations related to each scenario (initial and final) Navy personnel data (agility, age, weight, etc.)
<b>Scenario data</b> Number and description of the selected scenarios Crew and passenger operational procedures for each scenario Breakdown of each procedure in single tasks/actions Definition of functions used in each tasks/actions Description of each ship readiness state Initial ship watertight integrity condition (X, Y or Z)
<b>Simulation and output data</b> Selection of the results to produce Number of simulations to run
<b>Additional Data</b> EXODUS ID tags (alphanumeric identification labels) Parameters used in the Interface Software

Table 3.8.1 - Minimum data required by maritimeEXODUS to run personnel movement simulations.

The data included in Table 3.8.1 follow the MECE principle<sup>19</sup>: they represent mutually exclusive information and collectively exhaustive parameters. Therefore, the transferred data sets present no duplication of information, while all the relevant parameters are recorded. Since much of this information is not normally included in a SURFCON model, additional items had to be introduced (i.e. see Section 3.4). It should be noted that a small number of maritimeEXODUS-specific records had to be added to the usual PARAMARINE model description

<sup>19</sup> In probability theory a set of  $n$  events is said to be mutually exclusive if the occurrence of any one of them automatically implies the non-occurrence of the remaining  $n-1$  events. The same set of events is collectively exhaustive if at least one of the  $n$  events must occur [Minto, 2007].

to simplify and facilitate its translation to a maritimeEXODUS readable format.

These additional elements were introduced after an extensive investigation into alternative options for defining the required information from the PARAMARINE model description itself, using the specific algorithms embedded in the software. The solutions eventually adopted were very straight forward and, more importantly, permitted the maintenance of the model's flexibility as required in preliminary ship design. Some examples of these elements are (see also Figure 3.8.6):-

- a bounding box including all the DBB constituting the ship model;
- a series of DBB describing the horizontal and vertical ship compartmentation;
- a series of DBB representing the nuclear, bacteriological and chemical (NBC) compartmentation and Fire Zones subdividing the ship.

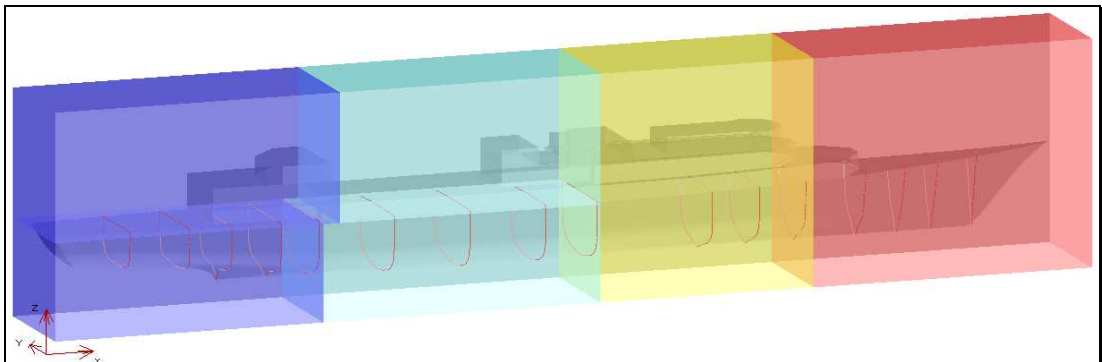


Figure 3.8.6 - A screenshot of the SURFCON model of a Type 22 Batch III frigate showing how the four subdivisions of the ship in Fire Zones (blue, cyan, yellow and red DBB) and its vertical compartmentation (red lines) are integrated in the model.

In transferring all the relevant information from PARAMARINE-SURFCON to maritimeEXODUS, the interface software tool resolved the many parametric links between Design Building Blocks. The complex design model was reduced to absolute locations of the geometry (the layout as 2D deck plans), vertical and horizontal connectivity items, (doors and hatches, ladders and stairs) and functional spaces (e.g. Operations Room and important equipment items, such as



gas turbines and liferafts). The instructions describing the scenarios to be simulated were defined in the SURFCON model in tabular form, so that they could be linked to the features of the ship design in the spatial model. This information was then transferred to maritimeEXODUS via a “scenario generator” tool, which generated the itineraries for each crew member in the simulation, starting from these simple instructions. Throughout this process no designer interaction was required. It is also important to note that no alteration of the representation of the ship description was required, thus maintaining the consistency of the models used by the ship design and analysis tools. This constituted the foundation upon which the compatibility of the input and output data has been assured.

Transferring the information from SURFCON to maritimeEXODUS and vice versa was not merely a syntax translation exercise. The process and the related software routines need to take into account the very different logic and philosophy behind the description of the same model in the two environments. The intermediate program developed was also able to manipulate the various output files produced by maritimeEXODUS into an acceptable format for the PARAMARINE model to process and for third parties tools to interpret and display (e.g. VRML viewers<sup>20</sup>).

### 3.9 User interface and visualisation of the results

As stated in the EPSRC project proposal [Galea and Andrews, 2004], PARAMARINE-SURFCON was expected to be used to visualise the results of maritimeEXODUS simulations in the context of the ship design. In addition to making use of the existing tabular displays of numerical results, the ship design

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<sup>20</sup> VRML viewers are standalone applications that allow viewing and manipulating Virtual Reality Modelling Language (VRML) models. VRML is a standard file format for representing three-dimensional interactive vector graphics [Web3D, 2008].

software should be used to present graphical representations of the results and to display images of output from the simulation.

Initially, the possibility of using existing functionalities of PARAMARINE-SURFCON software was investigated, resulting in a combination of existing functionalities being used to present the designers with the most relevant information on the simulations' performance. Two basic types of displaying the output data were used: the Tabular and Graph formats.

Figure 3.9.1 shows an example of the results of a set of simulations, rendered in PARAMARINE via a KCL macro. The left-hand hierarchy pane shows the complete set of results in a series of tables (i.e. the Tabular format). These tables provide, for each of the scenarios simulated, information on the performance of the overall ship population and each of the designated Functional Groups (e.g. Damage Control Organisation, Marine Engineers).

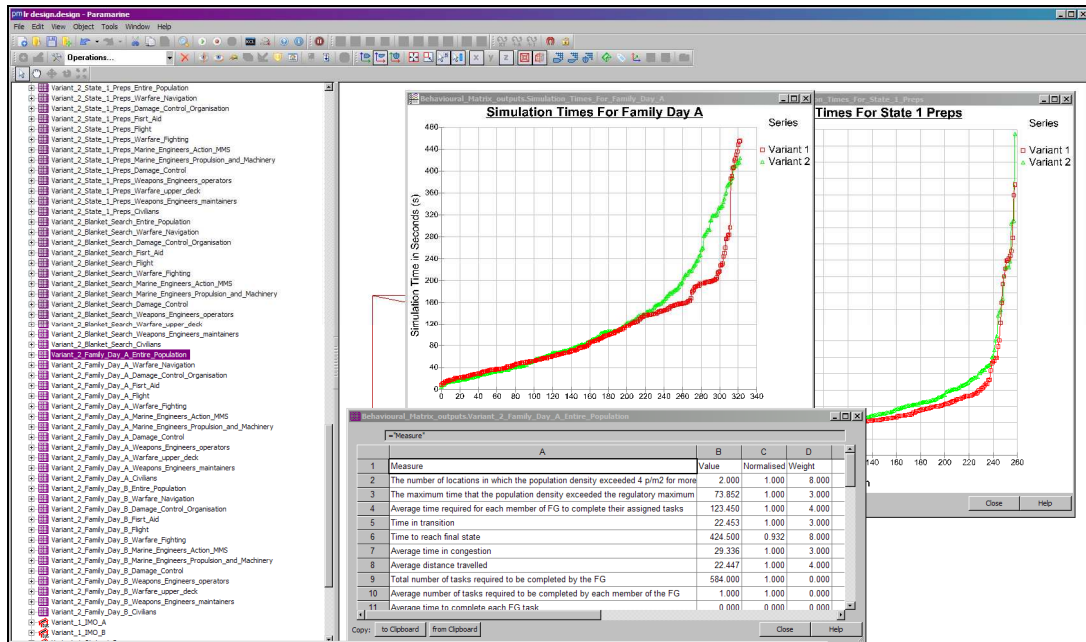


Figure 3.9.1 - The Screenshot of PARAMARINE-SURFCON showing tables and graphs populated with personnel movement simulation data.

Line graphs were used to display variations in numerical values. Figure 3.9.1 also shows the PARAMARINE-SURFCON implementations of line-graphs. In the example shown, the time taken to complete the scenario by each individual, is shown for two variants of the same basic design. Examining the graph of simulation times for the State 1 Preps scenario (<sup>21</sup>), it can be seen that Variant 2 performs more poorly when compared to the Variant 1 case. The graphs, in fact, that show a longer time is taken to achieve scenario completion and many more individuals are delayed in task completion in Variant 2 case. The use of relatively simple display techniques, such as line graphs, visually renders simulation generated information facilitating further investigation and fostering such use in design to assist design choices. Several alternative methods for visualising the results of the personnel movement simulations were incorporated into the developmental toolset (the interface software) and procedure. Interactive and intuitive interfaces, for investigating the results, were seen to be vital to put the numerical data contained in the HPMx into the context of the ship design and to readily inform and, perhaps, facilitate the decision making by designers.

The Software Development Plan had changed considerably by the end of the EPSRC research project (early 2008). The original plan was to create new PARAMARINE functionalities to accommodate the interfacing capability and to build a direct link between maritimeEXODUS and PARAMARINE. This would

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<sup>21</sup> State 1 Preps (i.e. State 1 Preparations) is the term used on a combatant ship to indicate the activities performed by the crew when a hostile attack is imminent or deemed probable or, as a preventative measure, for example when cruising in hostile waters and the possibility of air, surface or submarine attack is deemed particularly high. There are four degrees of readiness that a ship can assume, as illustrated in Table 2.6.1 (page 46), and each readiness (or preparedness) state corresponds to a specific NBCD asset (i.e. ship watertight integrity condition). During the preparations for State 1 the crew inspects the ship and checks that all compartments are correctly secured and ready for action. The term “State 1 Preps” is also (more formally) known as “Action Stations” and is also used in Royal Navy installations and bases, as well as Royal Air Force airbases and installations, and is equivalent to the United States Navy’s “General Quarters”.

have resulted in a richer data exchange between the two packages and an improved design experience. However, in the light of both the early investigations and subsequent developments, this was not found to be easily achievable by modifying the PARAMARINE software package. The solution identified to overcome these problems (i.e. the development of the interface software together with the use of third parties tools for the visualisation of the results) allowed investigations of different options to proceed with a greater degree of flexibility and complete independence from constraints likely to be imposed by a third party commercial software modification process.

The user interface, developed as an essential aspect of the research project, allowed reliable and consistent editing of operational and procedural data and linking this information to the SURFCON definition of the ship. Considerable effort was required to adjust the method of implementing the user interface to allow the ship designer to interact with a single design environment. This enabled the designer to devote more of their time to direct design activities, rather than being constrained by having to switch between different tools. Coping with different software packages and understanding their specific logic and philosophy, could not only distract attention from the main design process, but also be time consuming and consequently disincentivise the ship design from addressing HF issues at all in the preliminary design.

In the light of the above considerations, the user interface for the definition of all the data related to personnel operations, procedures and the W&SB was realised entirely within PARAMARINE by means of a series of tables implemented using PARAMARINE Version 5 [GRC, 2007a]. This feature allowed rapid selection and input of scenarios and procedures to be used for the simulations.

This user interface also facilitated the generation of a flexible and interactive visualisation of the results of those simulations. This method was developed in the light of an envisaged and eventually formally announced incorporation of MS Excel as a fully integrated object within the PARAMARINE-SURFCON environment. This software improvement considerably enhances the ease of use of the method developed by the candidate. It also allows implementation of some of the additional functionalities proposed in Chapter 6.

To ensure the design process would be informed by the results produced by the personnel movement simulations, the visualisation method was conceived with the aim of supporting the ship design decision making process. To achieve this, all the relevant information had to be extracted from the extensive data produced, which required logical organisation of the data and a clear presentation to the designer. This led to the development of a set of procedures for both post-processing and representing the results of maritimeEXODUS simulations using PARAMARINE-SURFCON. To demonstrate the usefulness and validity of a more comprehensive and interactive display of information, an additional tool was developed. This consisted of representing the ship design and the simulation outputs in a three-dimensional virtual reality environment, which allowed the end-users (i.e. the designer) to control and interrogate the model. This system not only reduces the risk of the designer being overwhelmed by a large volume of very specific simulation derived data, but also provides relevant information rather than raw simulation data. This aspect was seen to be particularly relevant in preliminary ship design when the design definition is very fluid and the integration of the simulated macro-ergonomics analysis needs to effectively and efficiently inform the designer.

The external visualisation environment was developed using the Virtual Reality Modelling Language (VRML). Originally known as the Virtual Reality Mark-up Language [Brutzman, 2006], VRML is a standard text file format for representing three-dimensional interactive vector graphics. VRML files can be viewed in any operating system and in any web-browser upon installation of appropriate plug-ins. There are several viewers available on the Internet for free download and use; in this research the Cortona VRML Client [Parallelgraphics, 2006] was used. VRML was chosen due to the numerous advantages it offers in terms of functionality, interactivity and capabilities.

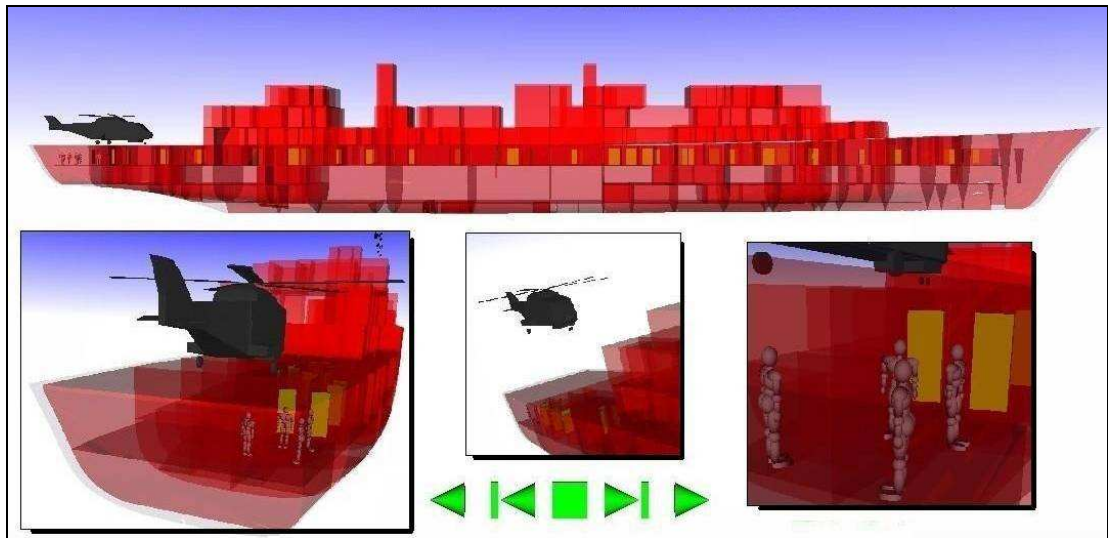


Figure 3.9.2 - A VRML example of the visualisation of the results. The 3D model is interactive and the simulation can be visualised as an interactive animation and “played” using the green buttons.

The most useful characteristics of the VRML with regards to the scope of work set for this research are:-

- Platform independence. The same code can be easily used in different operating systems (e.g. UNIX, Macintosh and Windows).
- Efficiency. VRML is a modelling language for specifying interactive animations. Text descriptions of geometries and associated characteristics are uploaded in memory and rendered locally using the plug-in viewer. Therefore, it has the

ability to work well on low-specification PCs with standard graphic cards and over slow-speed network connections.

- Selective refinement. VRML has the ability to add greater detail just to the portion of the scene or activity that requires it (i.e. the current view). This reduces considerably computational power demand and the load on the processor, while facilitating real time interaction with high quality graphical renderings.
- Hyperlinks. It is possible to add these links as properties of the modelled objects and have them associated with any graphical component; so these objects become selected and can be activated by clicking. They are similar to text and image hyperlinks, in that it is possible to connect them with other objects in the VRML scenes or with any other file type, application or web page.
- Texture mapping. It is possible to apply images to the surfaces of 3D objects to give them texture and realistic detail. Full colour (including transparency), lighting effects and animated images and videos can also be added as surfaces properties to the objects.
- Audio-Visuals. Object animations, sounds, images, videos and other aspects of a virtual environment (such as physics) can be embedded and the user can interact in a multi-dimensional virtual environment.
- Interactivity. Any VRML object can be programmed so that the user can interact in a number of modes. Users can also move their viewpoint or the relative position of any object in three dimensions.
- Compatibility. This technology can also be embedded in the most commonly used Office applications and used in a networking environment (i.e. multi-user mode). It also allows users to extract information from any of these applications and, importantly, from archives and database.
- Programmability. VRML is an object oriented programming language which is very easy to use and intuitive to code. A special Script Node allows also the addition of program code (e.g., written in Java or JavaScript) within the VRML file itself.

Additional information (in this case the identity of the watertight door under examination) can be shown through a pop-up dialogue (on the right hand side of Figure 3.9.3) that appears when hovering the mouse pointer over a specific element in the VRML environment.

The comparison between Figure E-8 (page 280) and Figure 3.9.3 (page 110) shows that this view can also be rotated and zoomed. In each of these figures, the footfall density map which is an animated image (i.e. GIF) representing a single maritimeEXODUS simulation, is superimposed on the design's general arrangement drawings (GA). In this visualisation all decks are on the same plane, but they can be manually shifted in the three dimensions in order to facilitate analysis of the information. In addition the VRML system developed as part of the research allows visualising the results of two competing designs in the same virtual reality environment. It is believed this would help the designer to see, interact, interrogate and understand the implications of their decisions on the vessel performance.

The vertical bars in the visualisation shown in Figure 3.9.3 provide a visual indicator of the maximum time the watertight doors (WTD) in specific locations were continuously open during the complete simulation of a scenario (e.g. "State 1 Preps" in Figure 3.9.3). The vertical bars can be programmed to display any other information the designer might require and, if appropriate, this information can be mapped on the relevant location of the ship. Examples of parameters that could be visualised include, for example, the maximum time a compartment has been occupied (i.e. manned), areas of peak congestion and average time spent waiting due to door/ladder congestion.



In addition to the animations of a complete simulation for each scenario, the system provides the visualisation of static images revealing cumulative measurements. For example, the footfall density maps in Figure 3.9.3 show the most congested areas in red and the least congested ones in grey (each visualisation is supported by a dashboard with the legend to numerically interpret the colour coding of the images displayed). This visualisation tool, developed by the candidate as a bespoke solution to achieve the aims of this research project, is believed to be particularly useful in examining the behaviour of the individual crew members in the simulation and relating this to the resulting numerical measurements, as is shown in Figure 3.9.2 and Figure 3.9.3 .

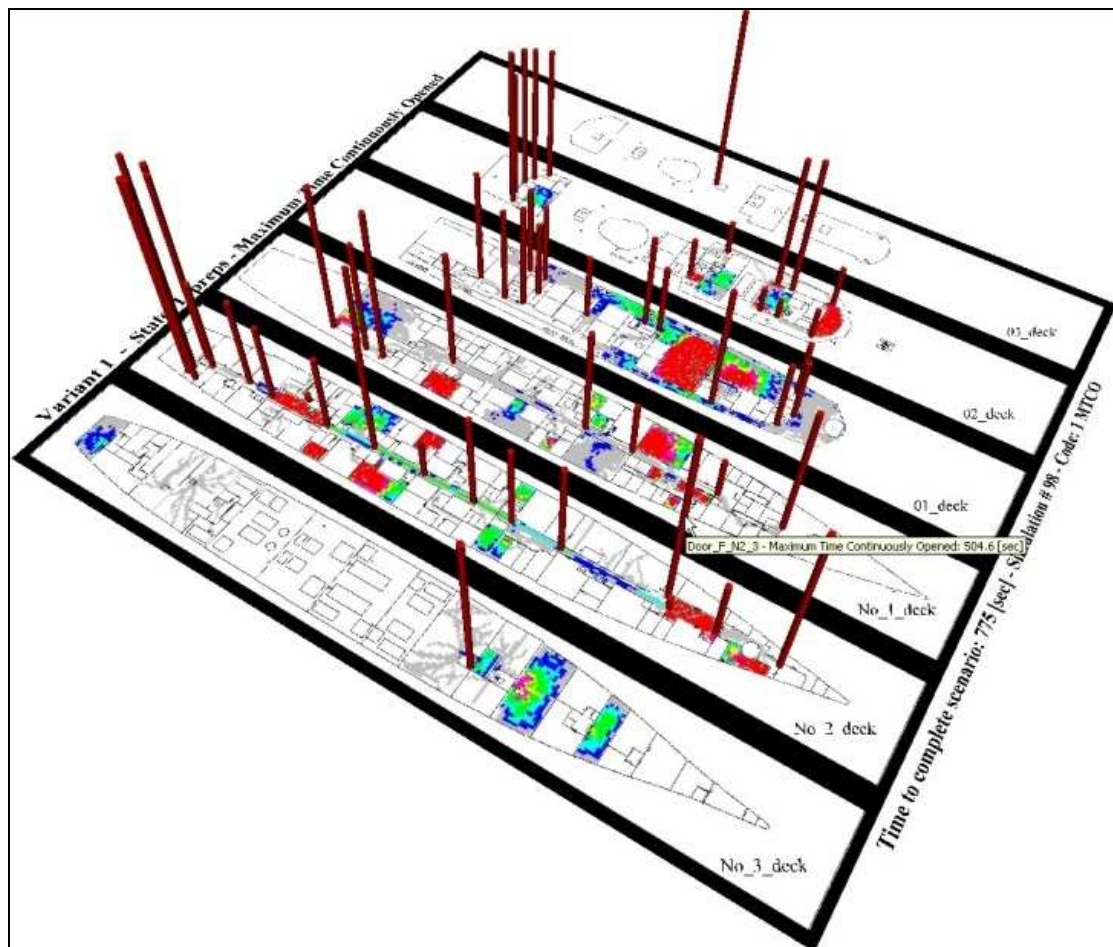


Figure 3.9.3 - Interactive visualisation tool using the VRML language showing a representative set of results (maximum time WTD were continuously opened). (Also shows pop up facility for a selected WTD).

As well as developing the new tools and providing an approach and guidance on the design of ships that could be directly used by the industrial partner (STG), the research was intended to provide GRC with an outline requirement for new functionalities to be introduced into PARAMARNE/SURFCON. To achieve this aim the finalised version of the VRLM interface, together with its description, was submitted to GRC Ltd. with a suggestion to implement similar capabilities in the next commercial version of their software [GRC, 2007b]. As a consequence, GRC announced the introduction of the texture map functionality, as it has a number of other applications beyond simulation results presentation [Forrest, 2008]. If this functionality could be controlled via the KCL macro system, then it will be possible to develop a new module of the interface software, capable of generating this new KCL macro, thus allowing simulation results to be viewed in the ship design software environment in a similar manner to that shown in Figure 3.9.2 and Figure 3.9.3 .

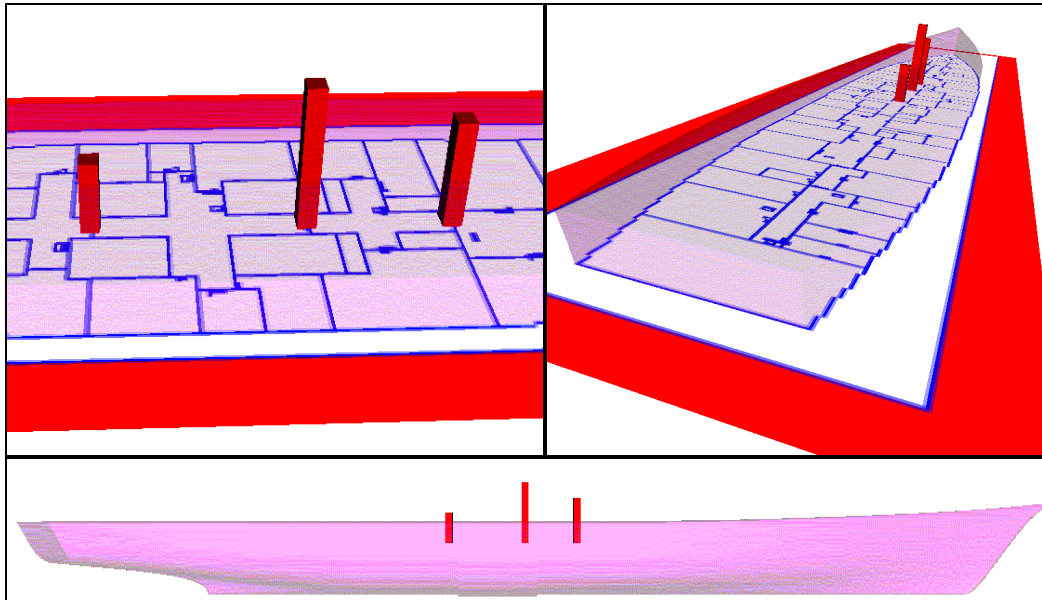


Figure 3.9.4 - Example of visualisation of results in the VRML environment: the columns indicate the time a single crew member spent operating WTD during a State 1 Prep. scenario.

In some respects PARAMARINE-SURFCON has already been modified by GRC to enhance graphical display of simulation outputs, following interim specifications and functionality solicitations by UCL DRC developed as part of the EPSRC research project. However, the concept of displaying these simulation results, overlaid on the ship design in an interactive manner, places the numerical analyses of personnel movement in context and should assist the designer in identifying the causes of poor performance and possible solutions or improvements.

The possibility of displaying personnel movement simulation results, superimposed on the ship design in an interactive environment, could also contribute to the better understanding by the designer of the operability and HF related characteristics of a given ship design. During the interface software development phase, several potential improvements and requirements for additional functionalities for both maritimeEXODUS and PARAMARINE were identified. These were sent to UoG FSEG [FSEG, 2007] and to GRC Ltd. [GRC, 2008] for further consideration. In particular, since the FSEG was UCL's partner in the EPSRC project and committed to enhance their software's capabilities [Galea and Andrews, 2004], some new functionalities were developed.

### **3.10 Modifications introduced by the interface software**

It was also considered that some of the current maritimeEXODUS software capabilities could be further improved to extract the maximum benefit from the interfacing of the two major software packages. For example, very early on in this research it was appreciated that the “node flooding operation” (NFL operation) could be improved. This had to be improved, since its current state could have severely penalised the progression of the research.

As mentioned in Section 3.3, maritimeEXODUS uses Object Orientated techniques and utilises a rule-based approach to control the simulation. These rules operate on a region of space defined by the geometry of the enclosure and, within maritimeEXODUS, such a geometry is modelled as a mesh of nodes. Each node represents a region of space typically occupied by a single person and the nodes are linked together in a mesh by a system of connections (i.e. arcs<sup>22</sup>).

Getting the DXF files (files containing boundary line information for the geometry) into maritimeEXODUS is the easy part of creating the geometry. Once imported, the geometry needs to be prepared before any simulations can be performed. More precisely, the geometry needs to be meshed with the network of nodes described above. Meshing the geometry manually can take a considerable length of time and effort, even using maritimeEXODUS's built in node flood operation (NFL). The NFL operation could have been dramatically improved, not only because its algorithms worked sufficiently well just with models developed manually and in maritimeEXODUS but also because this functionality had been developed as a support for the user (rather than as a fully automatic operation) however it still required a considerable user intervention. Furthermore, for example, as shown in Figure 3.10.1, even a simple geometry can be incorrectly meshed using the NFL operation. The opening on the bottom right corner of the geometry is, in fact, 0.7 m wide (i.e. more than enough to allow access to the inner area) but is not recognised by the algorithms behind the NFL module.

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<sup>22</sup> In maritimeEXODUS connections between two nodes are called arcs since the visual representation of these connections can be seen as an arcs between two squares representing the nodes (as shown, for example, in the image in Table C-5, page 244).

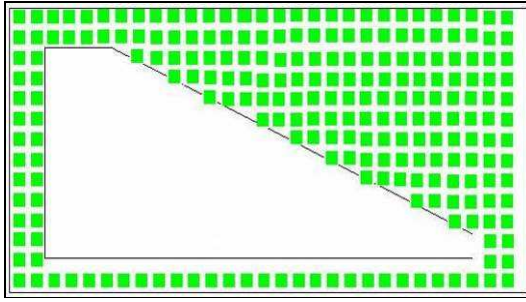


Figure 3.10.1 - Example of a meshing problem when performed with the NFL operation.

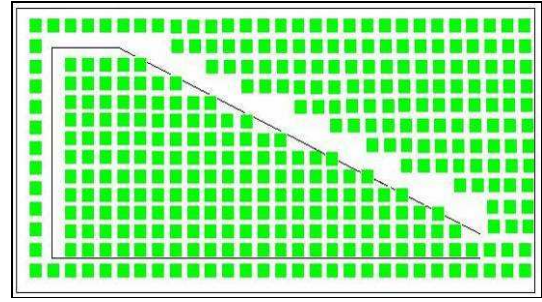


Figure 3.10.2 - Example of meshing performed with the ANFL operation.

This issue becomes a relevant problem when considering the Type 22 Batch III Frigate model. For example, when considering the complex geometry of the aft section of No 2 Deck, as shown in Figure 3.10.3, the result of such operation could lead to the meshing shown in Figure 3.10.4, with an incorrect meshing that will affect the personnel movement simulation in the portions of the geometry not meshed (i.e. left empty of nodes) not being accessible to the simulated crew.

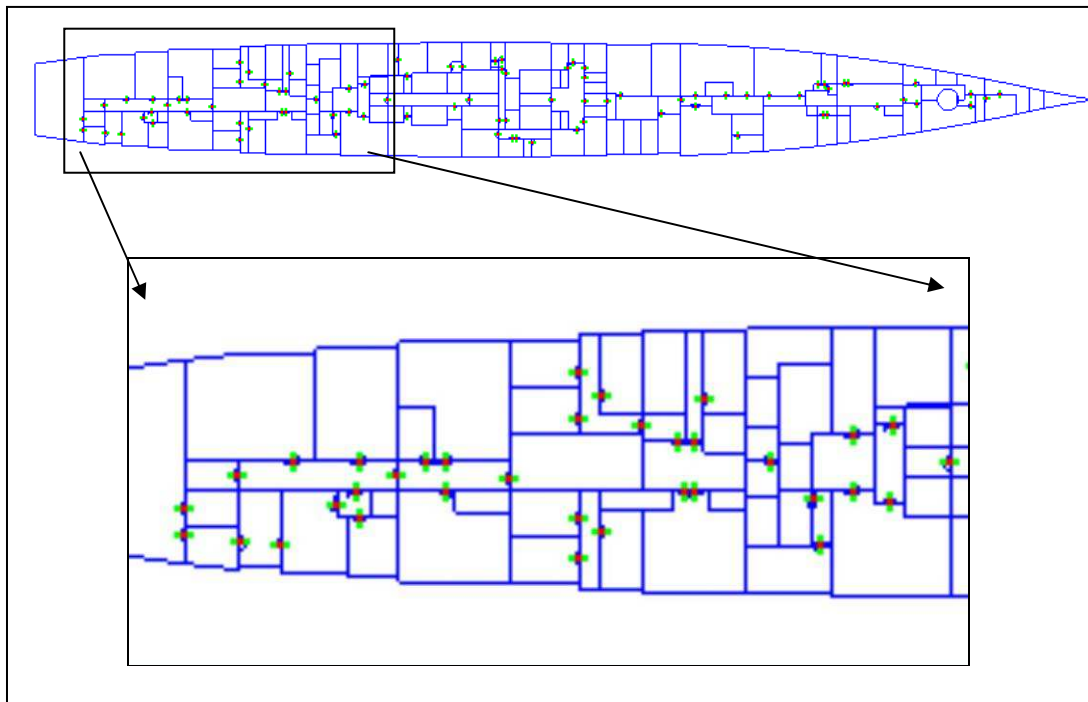


Figure 3.10.3 - Example of maritimeEXODUS' representation of geometry for No 2 Deck.

To solve this meshing problem, the candidate devised a novel solution that was implemented as a module in the Interface Software. This module is capable of

interpreting the SURFCON description of the geometry and generates the commands (i.e. NMTA instructions) necessary to force maritimeEXODUS to position nodes in every space of the geometry that might be used in the simulations. The results of the application of this new module (which is an integral part of the Automatic Node Flooding (ANFL) operation) to the simple geometry are shown in Figure 3.10.2, while its application to the more complex geometry of the Type 22 Batch III Fugate's No 2 Deck is shown in Figure 3.10.5. The remaining spaces that remain unmeshed are actually areas where personnel are not supposed to be at any stage of any simulation considered (e.g. air intakes, exhausts funnels, lift conducts, etc.).

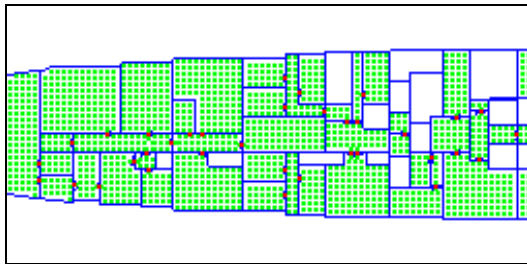


Figure 3.10.4 - Example of a meshing problem on No 2 Deck when using the NFL operation.

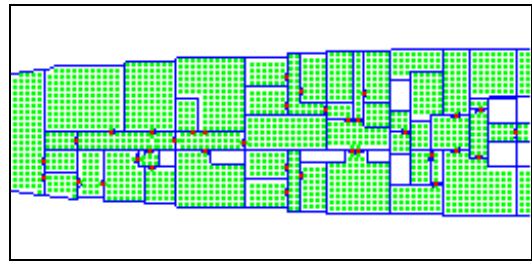


Figure 3.10.5 - Example of meshing No 2 Deck performed with the ANFL operation.

This newly developed feature (the ANFL operation) significantly reduces the time required to set up the geometry, greatly reduces the tediousness of the task and eliminates potential error. Previously, to set up a geometry of the complexity of those used in this work could conceivably take up to two man-weeks, however this innovative feature allows setting up geometries in a fully automated manner within in a few minutes.

The automatic flood operation, however, is not perfect as it is still based on the previous maritimeEXODUS NFL algorithms (the candidate had no possibility to re-program this core module in maritimeEXODUS, nor the FSEG team the

necessary resources). The ANFL feature starts each NFL operation from a node representing either a door or ladder, however these components (equipment items) may not be in optimal locations and could still lead to inefficiencies in the meshing and, potentially, could lead to parts of the geometry not being filled with nodes. Thus, although the automatic node flood operation is of great convenience and facilitates the achievement of the correct meshing in, potentially, 97% of the available geometry space, the user should still examine the geometry and may consequently need to recreate the node mesh in certain areas. However, this was not found to be necessary in the experiments done as part of the research. In addition, as described in Chapter 6, some further capabilities could be created: specifically, those which would allow both the correct simulation of naval crew performance and those enabling the output of additional significant feedback to the designer. A description of each of these desired capabilities was detailed in a functional specification submitted to FSEG for their consideration and use in developing future release versions of their software [FSEG, 2007]<sup>23</sup>.

Even though some of the required capabilities identified and described above for both maritimeEXODUS and PARAMARINE were not available during the research, the candidate managed to overcome some of the major limitations imposed by the two major software packages. This was achieved by developing prototype software, which considered these constraints as the initial and immutable conditions upon which to build the required integration tools. Some examples of this extra flexibility included in the prototype software include innovative algorithmic solutions, software “work-arounds” and the creation and use of a

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<sup>23</sup> The functional specification submitted to FSEG is of a commercially sensitive nature and, as such, is held by the UCL DRC in accordance with the procedures for handling confidential information. This document can be made available upon formal request and solely for the purpose of integrating the information contained in this thesis.

new programming language. Some of the main commands introduced by the new object-based programming language developed by the candidate are included in Appendix E.

The progress achieved allowed the development of a fully functional prototype system, together with the guidance related to its use and its integration into preliminary ship design.



## 4 - Application of the proposed approach

This chapter describes the application of the approach proposed and developed by the candidate, developed and described in Chapter 3. The new capabilities referred to include those introduced by the bespoke interface software, the enhancements to the simulation of personnel movement simulation software to encompass non-emergency scenarios, the use of the methods for the analysis of the output of the personnel movement simulations and the procedure developed for modelling and incorporating this new analysis capability into the preliminary ship design process.

### 4.1 The ship design models

The application of the proposed approach was tested using a PARAMARINE-SURFCON model of the RN Type 22 Batch III frigate. The operations described in Section 3.4 highlight the ship design definition activities that were carried out using Design Building Block approach and its realisation, the PARAMARINE-SURFCON software tool. This model was used as a baseline (BL) and was then developed into variant designs (e.g. VR<sub>1</sub>) which explored the impact of differing access arrangements and the level of design definition. Accordingly, such variants were developed by introducing changes in the ship's internal layout configuration and in the level of detail contained in the model.

The ship design model consisted of a Design Building Block configurational model representing the general arrangement of the ship. Associated with the model's building blocks were values of weight and space to represent a balanced ship design, as it would be produced during concept design studies [Andrews and Pawling, 2003].

The numerical characteristics assigned to the Design Building Blocks included:-

- Permanent weights that scale with ship size;
- Variable weights for ammunition and stores;
- Consumable fluids, supply and demand;
- Electrical power, supply and demand;
- Propulsive power, supply and demand.

Figure 3.4.2 (page 65) shows the Design Building Block model of the Baseline design, and Figure 4.1.1 compares the baseline Type 22 Batch III Frigate reference data (in red) and Design Building Block model (in blue), showing a close match in geometry for No 1 Deck (above) and No 2 Deck (below).



Figure 4.1.1 - Comparison between PARAMARINE-SURFCON model (in blue) and reference drawings (in red) for No 1 Deck (above) and No 2 Deck (below).

In addition to the numerical characteristics stored in the Design Building Block model, the design was assessed for resistance and propulsion and intact stability to ensure a naval architecturally balanced design was achieved. The naval architecturally balanced design was then maintained for any subsequent variant. The key aspect of this area of the research was that the resulting design model was not simply a general arrangement drawing, but a complete, numerically balanced, ship design description, which could be used to develop realistic design variants and, most importantly, would allow the procedures developed in this

research to be directly applicable to concept design studies on future Royal Navy vessels of interest to the MoD industrial partner (STG).

The main variant (Variant 1 - VR<sub>1</sub>) investigated the option of a double passageway on No 1 Deck and No 2 Deck replacing the single passageway of the baseline (BL). The primary access routes on these decks are shown in Figure 4.1.2 for the baseline and in Figure 4.1.3 for the variant design.

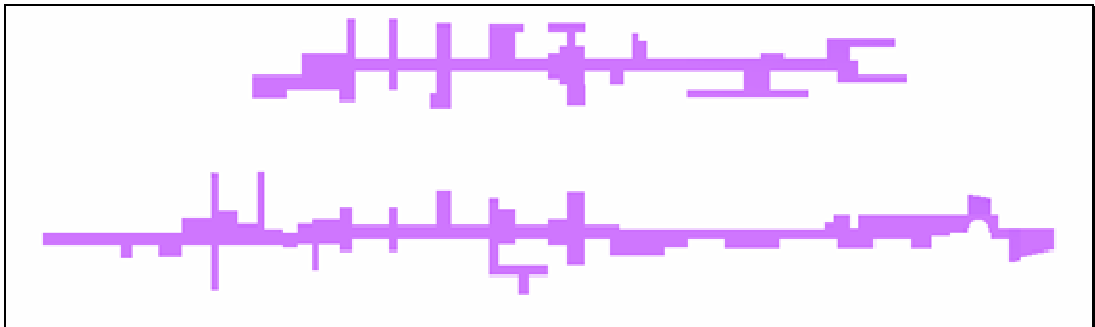


Figure 4.1.2 - The single passageway on No 1 Deck (above) and No 2 Deck (below) for BL.



Figure 4.1.3 - The double passageway on No 1 Deck (above) and No 2 Deck (below) for VR<sub>1</sub>.

The two ship design models (BL and VR<sub>1</sub>) represent balanced ship designs and the research aimed at defining them to a level comparable to that that would have been achieved during typical concept design studies. The geometric models, however, were produced to a level of definition greater than normal in concept design for a new design study. This was due to the process followed in producing the Type 22 Batch III Frigate model (i.e. modelling an already existing ship) but also because the two models had to be rendered suitable for the simulation of

personnel movement by the addition of a significant number of additional items (e.g. those modelling the connectivity between spaces in the design to facilitate personnel movement) as required by maritimeEXODUS. These features were modelled using existing PARAMARINE-SURFCON functionalities as described in Chapter 3, made use of the connectivity items listed in Table 4.1.1 and are described in more detail in Appendix C.

<b>Accessibility entity name in PARAMARINE-SURFCON</b>	<b>Equipment item description</b>
Door_SlidingDoor_Right_Ext	Internal sliding doors with normal and reduced height.
Door_SlidingDoor_Right_ReducedH	
Door_AntiClockwise_Pull_Reduced	Internal doors and double doors with direction of movement indicated. This direction is from the perspective of an individual standing on the circles shown inside each accessible space as shown in .
Door_AntiClockwise_Pull	
Door_Clockwise_Pull	
Door_AntiClockwise_Push	
Door_Clockwise_Push	Internal deck hatches with ladders. The deck notation is used to set the height of the ladder, based on the deck head height.
Hatch_from_02_deck_to_03_deck	
Hatch_from_01_deck_to_02_deck	
Hatch_from_No1_deck_to_01_deck	
Hatch_from_No2_deck_to_No1_deck	External doors with direction of movement indicated.
ExtDoor_Clockwise_Pull	
ExtDoor_AntiClockwise_Push	Emergency escape openings from the lower decks.
EmEscape_from_No3deck_to_No2deck	
EmEscape_from_No4deck_to_No2deck	Connection between two spaces with no door.
Arched_Opening_Placeholder	
Arched_Opening_Placeholder_Extended	External ladders. The deck notation is used to set the height of the ladder, based on the deck head height.
ExtLadder_from_No2deck_to_No1adeck	
ExtLadder_from_01_deck_to_03_deck	
ExtLadder_from_04_deck_to_03_deck	Internal 60 degree stairs. The deck notation is used to set the height of the stairs, based on the deck head height.
Stair_No2_deck	
Stair_from_01_deck_to_02_deck	
Stair_from_No2_deck_to_No1_deck	Upperdeck muster stations for evacuation scenarios.
MUST_ST_No3	
MUST_ST_No_2	

Table 4.1.1 - Examples of accessibility features included in the baseline (BL) and variants (e.g. VR<sub>1</sub>)

## 4.2 The operational design model

PARAMARINE-SURFCON was also used to develop a model of the operational aspects of the design. This is encapsulated in the watch and station bill (W&SB) which provides for each operating condition, where in the ship each individual must be and their role. The W&SB, which is described in more detail in Appendix D and in Appendix E, (under (5) Manning) also states the location of the individual crew member's accommodation. The operational design of the vessel was implemented by making use of existing PARAMARINE-SURFCON functionalities to define a standard method of representing the information that would be unambiguous and explicit, to allow the interface software to extract it from the model.

In the design models the W&SB was represented as a series of “spreadsheet objects” (i.e. PARAMARINE entity representing data in tabular format) with direct links or pointers to one another and to the Design Building Blocks representing the physical spaces and equipment items involved. Consequently, if the spatial configuration of the design was changed, then these pointers would continue to be linked to the correct Design Building Block, even if this is in a new location. Similarly, the disposition of the crew around the ship could be changed by redirecting the links within the spreadsheets to assign the crew to different Design Building Blocks.

It should be noted that, in PARAMARINE-SURFCON, the individual spreadsheet object, despite its name, is similar to a single table therefore cannot have multiple pages as, for example, in an Excel spreadsheet. This meant that 12 spreadsheet tables were used to represent the required information and these are described in Table 4.2.1. It was considered it would be more convenient for designers, to

use multiple specialised spreadsheets, rather than attempting to define all aspects of personnel movement in a single sheet.

Table name	Description
Setup	Defines the scenarios to be simulated, giving the start and end conditions (Readiness state, Ship Watertight Integrity Condition, watch status).
Personnel	The complete Watch and Station Bill defining the location of each crew member in each readiness state, accommodation, watch and Functional Group.
Waypoints	Translation table linking W&SB entries to the corresponding Design Building Blocks in the design.
State_1_Preps	Each of these spreadsheets summarises the objectives of individuals or groups in the scenarios. For example in “State_1_preps”, all crew members must proceed to their State 1 station, and fire fighting teams must form up and don protective gear.
Blanket_Search	
Family_Day_A	
Family_Day_B	
IMO_A	
IMO_B	
Whos_Who	Associates selected individuals to special groups such as fire-fighters.
Actions	Allows a definition of delay times for special actions (e.g. donning protective gear) in simulations.
Rank_Rate	Defines a priority hierarchy based on the rank and rate (which are declared for individuals in the W&SB), permitting more realistic simulation of crowd behaviour on naval vessels.

Table 4.2.1 - Summary of the tables used to define the operational design of the vessel in PARAMARINE-SURFCON.

### 4.3 Levels of design detail

An important aspect of the Design Building Block models which is that they should be consistent with the design description likely to be available in concept design studies. However, the baseline model produced in this exercise is significantly more detailed than has typically been the case in previous UCL DRC concept design studies, such as the LCS and Mothership studies, when numerically compared with the Type 22 Batch III BL model (as summarised in Table 3.4.2).

By comparing Figure 4.3.1 and Figure 4.3.2 the difference is apparent in the level of detail in the general arrangement of these extracts from each design. The higher level of detail of the BL model not only increased the time taken to define the baseline ship, but it also significantly increased the time and effort required to produce balanced variant designs, as the number of interactions and links, explicit and implicit, between Design Building Blocks that must be considered when the design is altered.

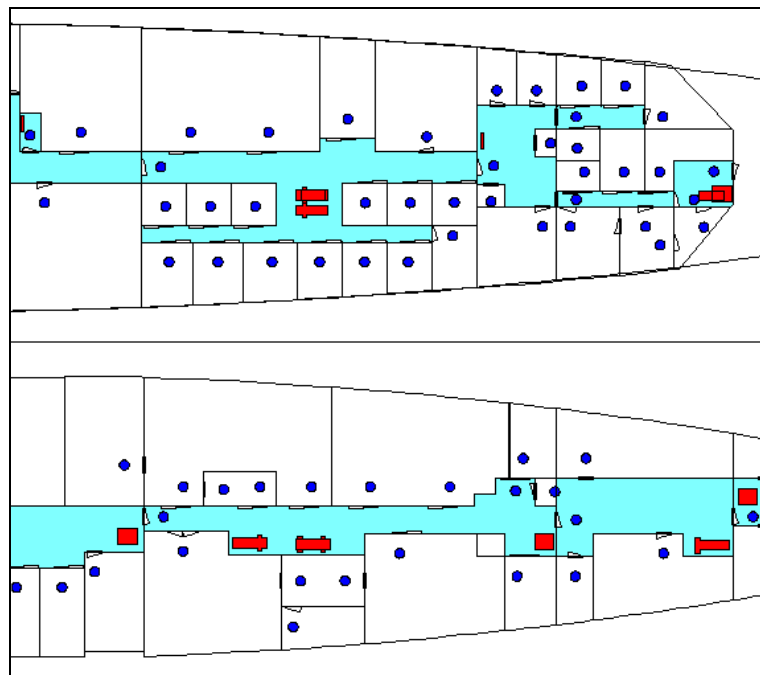


Figure 4.3.1 - The Type 22 Batch III baseline, showing high level of detail and with access routes and connectivity items highlighted.

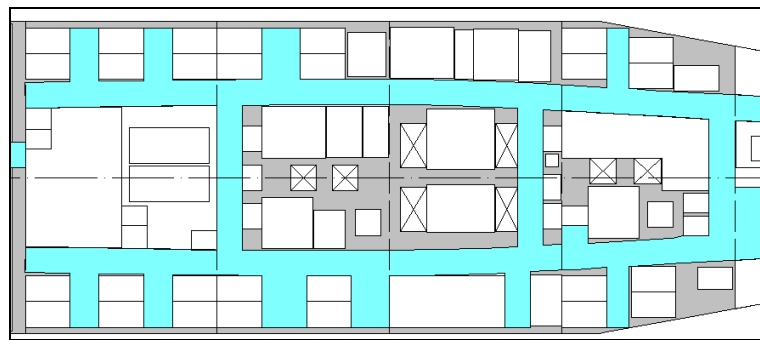


Figure 4.3.2 - The UCL LCS trimaran, example of the maximum level of detail modelled in concept ship design with access routes and unallocated space highlighted [Andrews and Pawling, 2006b].

In addition to the difference in the level of detail between the models of the UCL LCS trimaran and the Type 22 Batch III BL visible when comparing Figure 4.3.1 and Figure 4.3.2, there would seem to be three main differences:-

**a) Access routes.** Firstly, the access routes, which are highlighted in cyan in both figures. In the UCL LCS model these are simple, showing the overall access philosophy, with constant passageway widths, whereas in the Type 22 Batch III Frigate model the passageway width is variable and the arrangement has deviated from the overall access logic over the many design iterations required to detail the design for construction.

**b) Connectivity items.** The second main difference is in the inclusion of connectivity items required for the simulation of personnel movement. These are highlighted in Figure 4.3.1, specifically ladders and stairs (in red) and doors and hatches (in blue). The latter also show the points generated by the interface software that lie within each space on the General Arrangement and can thus be used to explicitly identify spaces (see Section 3.4, point 4 and Figure 3.4.3).

**c) Unallocated space.** The final issue is the inclusion of unallocated space in early stage design. In Figure 4.3.2 the unallocated space is shown in grey. In a complete ship design (such as the Type 22 Batch II Frigate) these unallocated spaces would usually be included within other functional spaces, making the latter slightly larger than the initial numerical estimates of required size used in concept design. In the Type 22 Batch III baseline model, these unallocated spaces are not present. This can be ascribable to two factors: firstly, to the way in which the design model was produced (i.e. modelling a ship from its GA drawings) and secondly to the additional complexity in the access routes modelled in the baseline.



### **4.3.1 Design models resolution (High, Medium and Low)**

In order to utilise the new capability for personnel movement performance assessment in concept design, the sensitivity of the procedure and simulation tools to a changes in the level of detail was considered. Both the baseline (BL - single passageway) and first variant (VR<sub>1</sub> - double passageway) designs were modelled at three levels of detail: High, Medium and Low.

#### **High Resolution (HR)**

This model, shown in Figure 4.3.1, represented the level of detail provided from the General Arrangement drawings of the ship “as built” therefore achieved a significantly higher level of detail than would normally be reached in concept design.

#### **Medium Resolution (MR)**

This model, shown in Figure 4.3.3, represented the maximum level of detail that would normally be produced in concept design. The overall geometry matches the detailed model but certain items, such as equipment lockers, are not modelled and groups of cabins are represented as a single block. The candidate modelled the medium resolution baseline design (BL-MR) starting from the high resolution baseline model (BL-HR) and reducing its level of detail definition.

#### **Low Resolution (LR)**

This was a greatly simplified model, as shown in Figure 4.3.4 in which only the main bulkheads and access routes were included in the geometric description of the ship. This model represents the level of detail that would be available in the early stages of concept design, when it would be possible to roughly define what deck and compartment each of the key spaces are in, and to select an overall access style.

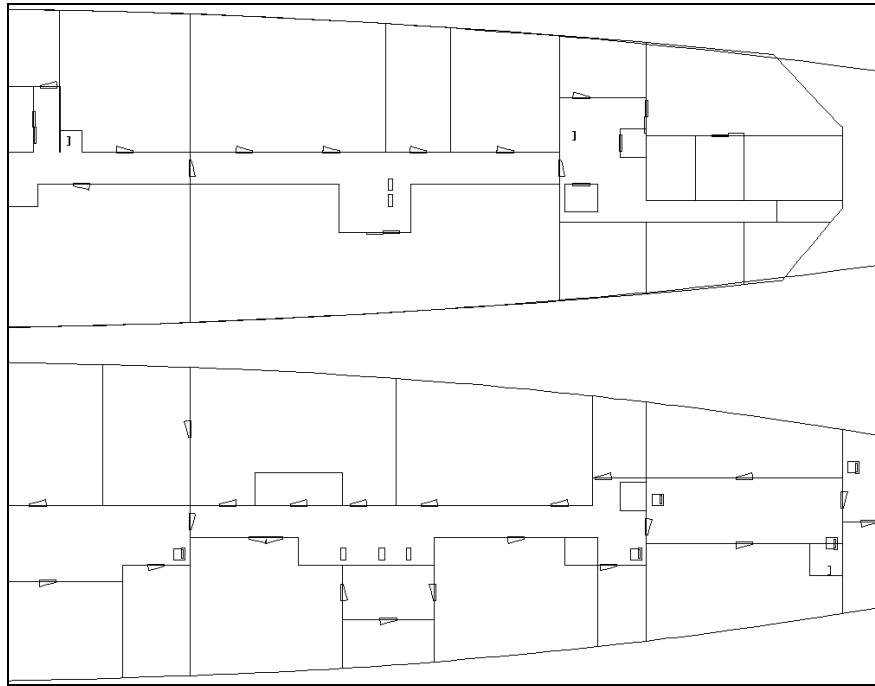


Figure 4.3.3 - Example of the level of detail in the Medium Resolution model of the baseline design.

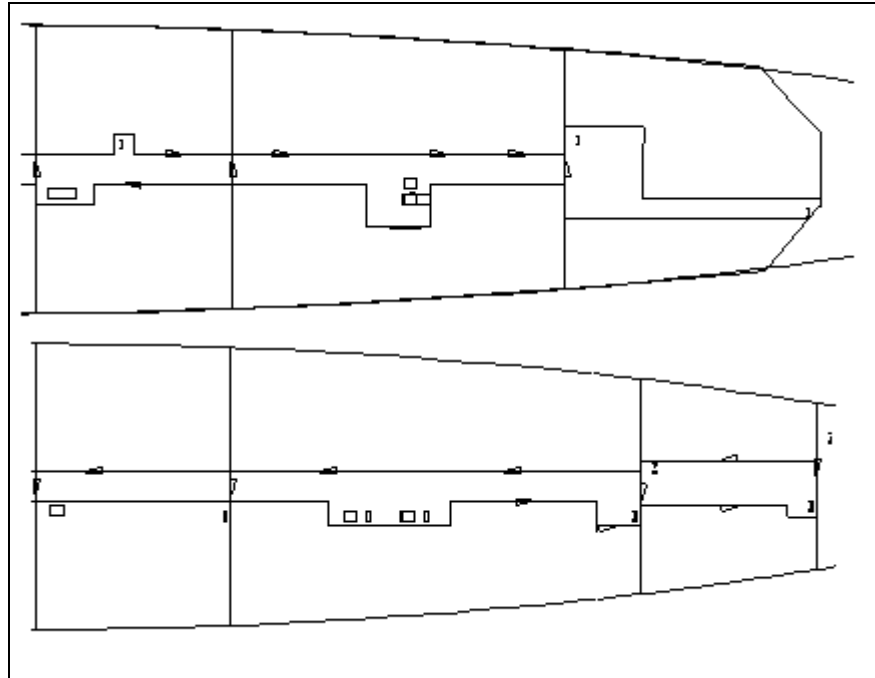


Figure 4.3.4 - Example of the level of detail in the Low Resolution model of the baseline design.

## 4.4 Example of the application of the proposed approach

To demonstrate the feasibility of the approach proposed and to show that the concept of using the integrated software iterations incorporating human simulation with ship configurational design is achievable, a detailed experiment plan was devised and followed as in Section 4.4.1 .

### 4.4.1 Outline of Investigation

The structure of the investigation is shown in Figure 4.4.1 (for the parallel approach) and in Figure 4.4.2 (for the serial approach). Figure 4.4.1 shows the eight design models with their design changes (horizontal axis) and resolution level (qualitatively indicated by the vertical axis). In this representation, the investigation to be conducted is indicated by the black arrows which represent a comparative analysis between the two connected designs. The letters indicate the type of investigation performed and Table 4.4.1 describes the aim of each experiment.

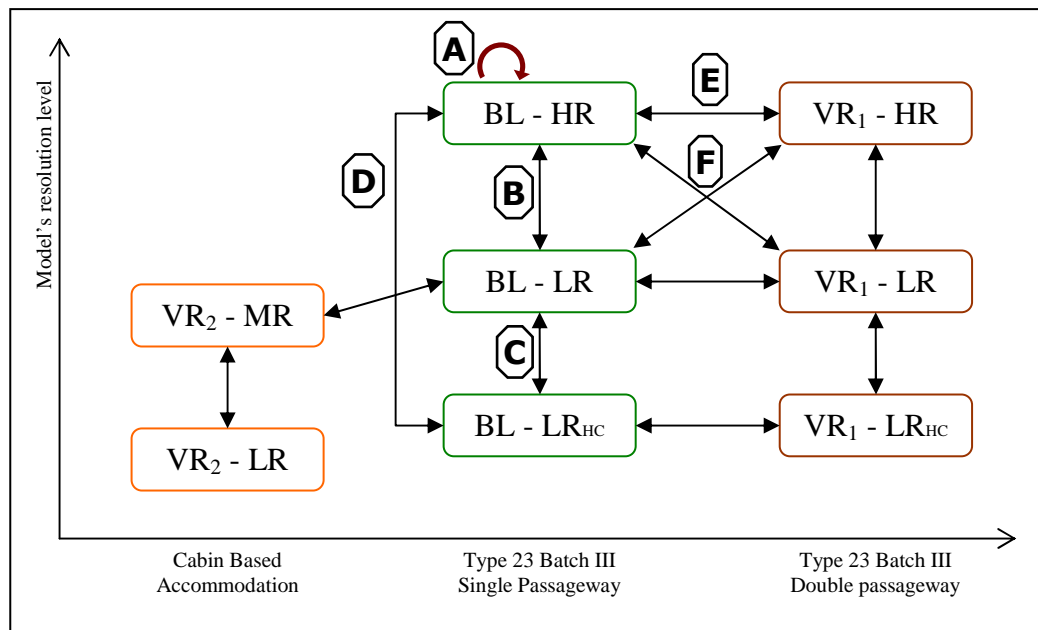


Figure 4.4.1 and Figure 4.4.2 - The process to investigate the parallel approach.

In Figure 4.4.1, BL indicates the Baseline model (that of the Type 23 Batch III as build i.e. with a single passageway), VR<sub>1</sub> indicates the first variant design of the Type 23 Batch III (the variant of the BL model with a double passageways No. 1 and 2 Decks), VR<sub>2</sub> indicates a second variation of the baseline design introducing the Cabin Based Accommodation style. High, Medium and Low resolution models are indicated by HR, MR and LR respectively. The index HC (e.g. BL-LR<sub>HC</sub>) indicates a model where all types of horizontal connectivity items have been replaced by a single item, for example, with a non-watertight door.

In accordance with the investigation, two variants of the Type 22 Batch III frigate have been created: VR<sub>1</sub> (with the double passageway configuration) and VR<sub>2</sub> (with Cabin Based Accommodation style). These variants of the Type 22 Batch III frigate were used with varying levels of definition to see which one would perform the better and whether the conclusions drawn from the HF analysis would be consistent with the expectations (i.e. aligned with real life experience).

The investigation outlined not only to investigate and show that the principles of the integration are viable and the results are meaningful for the designer, but also to gain a better understanding of the procedure developed and its possible applications. Ultimately, this set up investigations to indicate the possibilities in exploring the design space in preliminary ship design by showing the results of significant examples of the integration of personnel movement simulation.

Type of investigation	Aim of the investigation
<b>A</b>	Evaluation of the operational performance of a single model. This should provide raw data in the HPMx. These types of experiment aimed at developing the visualisation and investigating the options for the interpretation of the results.
<b>B</b>	Investigation as to whether reducing the level of detail maintains the consistency and accuracy of the results. This type of comparative analysis was tested to assess if the same design modelled with different detail levels produce similar results.
<b>C</b>	Investigation as to whether a further reduction in number and variety of the details in the model would maintain the accuracy of the results. For example, they can be seen as sensitivity tests to determine how influential the <u>types</u> of horizontal connectivity items can be. In addition, these investigations can test how sensitive the results of the simulations are to the <u>position</u> of horizontal connectivity items.
<b>D</b>	This investigation aims to show that the serial approach is valid i.e. in investigating to what extent the level of detail can be reduced without compromising the validity and significance of the simulations' results. In particular these types of investigations are aimed at whether (and to what extent) the proposed approach has transitive properties <sup>(24)</sup> .
<b>E</b>	Testing the capability to compare two models with similar levels of definition. These experiments should produce plausible results and the results should reasonably match real life experience.
<b>F</b>	This is to test the possibility of comparing different models with different layouts and levels of different resolutions.

Table 4.4.1 - Description of the aim of each type of investigation indicated in Figure 4.4.1.

Type C investigations (in Table 4.4.1), was performed on models where all types of horizontal connectivity items were replaced by a single type of connectivity item, which showed that the overall difference in the vessel's performance (indicated by the HPMx) is acceptable. This suggests that there is the possibility of automating the process of placing horizontal connectivity items in the model. This holds the promise of considerably reducing the designer's effort to render the model suitable for the simulation of personnel movement by eliminating the

<sup>24</sup> In general terms, a mathematical operation ( $\phi$ ) possesses a transitive property of equality (or equivalence) if whenever an element A is related to an element B, and B is in turn related to an element C, then A is also related to C – In mathematical terms if  $A \phi B$  and  $B \phi C$ , then  $A \phi C$  ([http://en.wikipedia.org/wiki/Transitive\\_relation](http://en.wikipedia.org/wiki/Transitive_relation)).

need to manually add a significant number of items in the design model. Similar experiments were conducted on vertical connectivity items, but early investigations in this matter showed little opportunity for replacing them with a single type of vertical connectivity item as the simulation algorithms appear to be very sensitive to any such variation.

Figure 4.4.2 show a sub-set of investigations (Type B - see Table 4.4.1) as to whether the proposed approach has transitive properties and to what extent this properties can be maintained valid, by testing the validity of following statements:

- if the approach allows comparing design  $D_1$  and  $D_2$ ;
- and if the approach allows comparing design  $D_2$  and  $D_3$ ;
- then the approach allows comparing design  $D_1$  and  $D_3$ .

In the above statement, the phrase “if the approach allows comparing design  $D_1$  and  $D_2$ ” means “if the HPMx of  $D_1$  and that of  $D_2$  have overall vessel performance indices (i.e.  $VP_{D_1}$  see Section 3.6.1 and Table 3.6.2 at page 85) that are not significantly different from each other and if the evaluation scenarios scores (ESS) of the two variant designs (i.e.  $D_1$  and  $D_2$ ) are not significantly different (taken to mean that they differ by less than 10%)”.

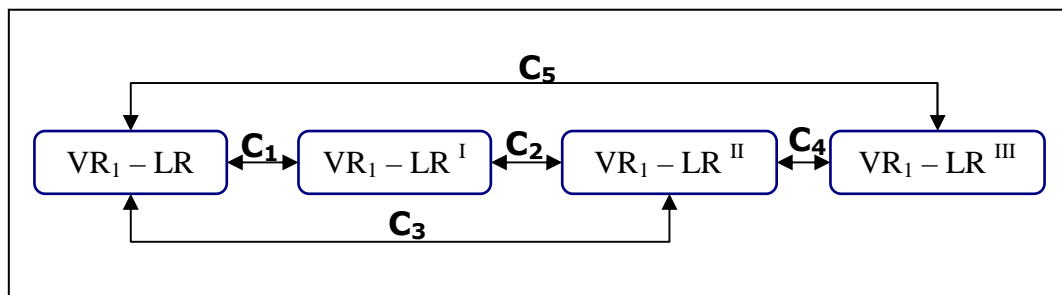


Figure 4.4.2 - The process to investigate the serial approach.

It was also planned to push the testing phase even further by performing all the investigations necessary to find out what would be the minimum level of the design model definition (i.e. the granularity level of the design model) that does not compromise the validity of the principle mentioned above (i.e. the transitivity property of the proposed approach) as illustrated in Figure 4.4.2. This sub-set of experiment considered the VR<sub>1</sub> - LR and three other models obtained by progressively reducing the level of detail in each model (i.e. VR<sub>1</sub> - LR<sup>I</sup>, VR<sub>1</sub> - LR<sup>II</sup> and VR<sub>1</sub> - LR<sup>III</sup>).

The investigations condensed the validity of following statements “if the approach is valid in performing C<sub>1</sub> and C<sub>2</sub>, then it is valid in performing C<sub>3</sub>” and, more importantly, to what level of model definition and under which conditions is true that “if the approach is valid in performing C<sub>1</sub>, C<sub>2</sub> and C<sub>3</sub>, then it is valid in performing C<sub>5</sub>”. In these sentences, the concept of validity means that the HPMx result in vessel performance indices (see Section 3.6.1) that are sufficiently similar to each other and if the evaluation scenarios scores (ESS) of the two variant designs examined show sufficient alignment (e.g. within a 5% difference).

Additional sensitivity studies on the proposed approach undertook simulations on design models differing in:-

- 1) layout (and geometry features),
- 2) W&SB (e.g. manning levels, reallocation of tasks<sup>25</sup>), or
- 3) scenario definitions (e.g. operating procedures<sup>26</sup>).

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<sup>25</sup> For example when tasks allocated to one crew member are split between two crew members.

<sup>26</sup> For example when the sequence of actions defining a specific operating procedure (part of the scenario definition) is modified by rearranging the order in which the tasks need to be completed, by adding new tasks or by removing some tasks.

Further insights could have been obtained by combining these three types of changes and analysing their collective effect. Unfortunately, due to time and effort and to the technical limitations described in Chapter 3 (see Sections 3.2, 3.3, 3.6 and 3.8), this was not possible. However, significant results and insights have been gained and the data, information and experience were circulated among the UCL DRC team, recorded in the DRC's database and are available for further research to be conducted on the topic, as presented in Chapter 6.

#### **4.4.2 The scenarios**

To gauge vessel performance across a range of criteria, the list of Evaluation Scenarios (ES) can be divided in two categories as shown in Table 4.4.2: emergency scenarios (EMS) and normal operations procedures (NOP scenarios). NOP scenarios represent situations where the ship's crew move around the vessel carrying out specific tasks. An example of a NOP scenario for a naval vessel is the 'State 1 preps'. In this ES the naval vessel is prepared for a war fighting situation.

This scenario disregards the normal non-essential tasks and brings the organisation of personnel, equipment, machinery and water tight (WT) integrity to the highest state of preparedness and readiness to deal with any emergency that might occur. Another example of a NOP scenario is the "Blanket Search" scenario where the ship's complement searches every compartment onboard for, for example, potential damage or intruders.



<b>Evaluation Scenario (ES identifier)</b>	<b>Scenario's name</b>
<b>EMS</b>	
ES <sub>1</sub>	Action stations
ES <sub>2</sub>	Normal Day Cruising A
ES <sub>3</sub>	Normal Day Cruising B
<b>NOP scenarios</b>	
ES <sub>4</sub>	State 1 Preps
ES <sub>5</sub>	Blanket search
ES <sub>6</sub>	Family Day A
ES <sub>7</sub>	Family Day A

Table 4.4.2 - Example list of evaluation scenarios (ES).

The emergency evacuation scenario involves all onboard preparing to abandon the vessel. In many cases, the onboard personnel are expected to gather at emergency stations prior to abandoning the vessel. The “Naval Ship Code” [INSA, 2010] recommends that evacuation analysis be undertaken with the crew initially located in three different states, “normal day cruising”, “normal night cruising” and “action stations”.

In the ‘normal day cruising’ scenario the crew locations are not necessarily known due to the relaxed nature of the vessel, although they would generally be within a particular region for example within a certain water tight zone. Only ¼ of the complement on current watch would be closed up, the rest could be in their cabins, in mess rooms or elsewhere onboard the vessel. In the evacuation scenarios for naval vessels, once the relevant call is made, each crew member moves to their emergency stations and await the command to abandon the vessel.

Table 4.4.2 presents a selection of ES that can be used to assess the performance of naval surface combatants from the point of view of personnel movement. The evacuation scenarios employed within the example application

demonstrated in this research are based on the Naval Ship Code 'Normal day cruising' and 'Action Station Evacuation' scenarios while the NOP ES are the 'State 1 Preps', 'Blanket Search', 'Family Day A' and 'Family Day B' scenarios.

Each of the designs considered has the Type 22 Batch III Frigate a complement of 262. The crew are initially located where they would be expected to be at the start of each scenario as determined by the "state" of the vessel. Crew members not on watch are located in their cabin. Each variant was assessed using the seven ES in Table 4.4.2 .

The NOP scenario 'state 1 Preps' (ES<sub>4</sub>) involves the entire complement moving to designated locations throughout the vessel and changing into appropriate battle gear. In addition, two teams of five fire fighters in the Damage Control and Fire Fighting FG (FG<sub>2</sub>) move to their appropriate Fire Stations where they check all the fire fighting equipment and dress in full Fearnought clothing. At the same time, four crew members from FG<sub>2</sub> close all WTD on the vessel. The 'blanket search' scenario involves the crew searching the entire vessel for damage. Each crew member searches the compartment they currently occupy while eight crew members search all the unoccupied compartments. 'Family Day A' involves a number of untrained civilians on board the vessel when an incident occurs.

The civilians are ushered to the muster stations while the crew move to their emergency stations in preparation in tackle the incident. In 'Family Day B', the incident engulfs the entire vessel and the command is given to evacuate, at which point the crew move to join the civilians at the muster stations. In both designs (BL and VR), the same procedures are employed so the results produced from the HPM will be a direct result of the differences in vessel layout.

The evacuation scenario ES<sub>1</sub> involves the complement moving from their normal day cruising locations towards their designated emergency stations ready for the call to abandon ship. The evacuation scenario ES<sub>2</sub> then involves the complement moving from their emergency stations to the muster stations where they will collect vital lifesaving equipment prior to evacuating. The evacuation scenario ES<sub>3</sub> involves the ship's complement moving from their action stations to the muster stations.

It must be noted that the scenarios used are not intended to accurately model actual naval operations, but to be sufficiently close to be representative and meaningful to designers.

#### **4.4.3 The weighting coefficients**

Typical ES and PM weighting used in the analysis are shown in Table 4.4.3 and Table 4.4.4 respectively. The weightings were derived in consultation with the MoD (STG Liaison Officer, Lt. Cdr. Boxall P.). The NOP scenarios were given higher weightings than the evacuation scenarios, since they are perceived to be less important to a naval vessel design than NOP scenarios.

Furthermore the evacuation scenarios are considered pass/fail scenarios, so the vessel must meet the required evacuation standards if they are to be considered acceptable.

#### 4.4.4 Results of investigations into Design Variants (High Res.)

This sub-section presents the results of the investigations on BL-HR and VR<sub>1</sub>-HR.

The layouts of the two main decks of the two High Resolution (HR) models are shown in Figure 4.4.3.



Figure 4.4.3 - Passageways (in purple) and deck connections (red circles) on two main decks of the baseline and variant 1 designs.

Each of the seven evaluation scenarios (i.e. ES<sub>1</sub> - ES<sub>7</sub>) were run 50 times using the maritimeEXODUS software and the most representative simulation result files were selected for each scenario to construct the HPMx for each design. The Performance Measures (PMs) for both designs were then determined and the final HPMx constructed as shown in Table 4.4.3.

<b>Evaluation scenario</b>	<b>Scenario Weight</b>	<b>BL</b>	<b>VR<sub>1</sub></b>	<b>% difference between BL-HR and VR<sub>1</sub>-HR</b>
<b>Normal Day Cruising A</b>	1.0	46.14	44.33	3.93%
<b>Normal Day Cruising B</b>	1.0	50.81	46.79	7.92%
<b>Action Stations Evacuation</b>	1.0	51.45	46.70	9.23%
<b>State 1 Preps</b>	1.5	67.46	75.47	-11.87%
<b>Blanket Search</b>	1.5	78.04	84.29	-8.01%
<b>Family Day A</b>	1.5	48.65	47.20	2.99%
<b>Family Day B</b>	1.5	56.03	55.32	1.26%
<b>Overall performance of design (VP)</b>		523.7	531.2	

Table 4.4.3 - Example of HPMx (high level, with evaluation scenario scores) for two high resolution (HR) designs.

Table 4.4.3 shows how the BL-HR results are combined to produce an overall performance score of the design (the Vessel Performance (VP) score) of 523.7 while those from VR<sub>1</sub>-HR produce a VP score of 531.2. Thus we note that the overall performance of both variants is broadly similar, with BL-HR producing a marginally better (1.4%) overall human factors performance according to the measures used.

Furthermore, VR<sub>1</sub>-HR outperformed BL-HR in most of the scenarios, however BL-HR significantly outperformed VR<sub>1</sub>-HR in two NOPs and the worst performing scenario for BL-HR is the ‘Action Stations Evacuation’. As BL-HR produces the better overall performance and produces significantly better NOPs performance it would be consider the design of choice. However, both designs performances might be further improved by investigating, for example, the reasons behind the poor performance in their worst performing ES.

Clearly this analysis and conclusion from it are based on a particular selection of Evaluation Scenarios, Performance Measures and Weightings that have been used in the analysis. If the factors used to measure crew/vessel performance (i.e. the

Performance Measures) or the particular scenarios (i.e. the evaluation scenarios) might then suggest conclusions of a different nature.

To better understand why VR<sub>1</sub>-HR out performed BL-HR in the 'Action Stations Evacuation' scenario (ES<sub>3</sub>) and to identify potential areas in which BL-HR can be further improved it was necessary to investigate the sub-components of the HPM. Presented in Table 4.4.4 are the PM scores for BL-HR and VR<sub>1</sub>-HR for ES<sub>3</sub>.

BL-HR performed better than VR<sub>1</sub>-HR in five of the 18 PMs (G<sub>2</sub>, G<sub>5</sub>, M<sub>1</sub>, M<sub>14</sub> and M<sub>16</sub>) and of these five PMs, four show at least 10% better performance than the respective VR<sub>1</sub>-HR PM, with M<sub>14</sub> (i.e. the most the times a WT door was operated) and M<sub>16</sub> (i.e. average number of doors used per person) returning 18% better performance. However, 12 of the PMs for BL-HR returned poorer performance than VR<sub>1</sub>-HR. Of these PMs nine gave values which were at least 10% worse than those in VR<sub>1</sub>-HR. The poorest performance was achieved by G<sub>4</sub> (i.e. average time spent in congestion) which returned 50% worse performance.

It is interesting to note that the poor return produced by VR<sub>1</sub>-HR for M<sub>1</sub> (i.e. number of WT doors used in the scenario) is due to the dual corridor system having some eight more WT doors than the single corridor variant. The increase in the number of WTDs is due to the requirement to maintain watertight integrity and so is dictated by a design constraint which cannot be violated. The time spent travelling is affected by factors such as the walking speeds of the individuals, the type of terrain they pass through (i.e. ladders, corridors, stairs, etc.) and the congestion they experience on the way.

FG1 – Entire Population		BL-HR		VR <sub>1</sub> -HR	
	Weight	Raw	Norm	Raw	Norm
<b>CONGESTION CRITERIA:</b>					
C1 - The number of locations in which the population density exceeds 4 p/m <sup>2</sup> for more than 10% of the overall scenario time'	8	4.00	1.00	4.00	1.00
C2 - The maximum time that the population density exceeded the regulatory maximum of 4 p/m <sup>2</sup> for 10% of the simulation time	3	75.40	1.00	42.14	0.56
<b>GENERAL CRITERIA:</b>					
G1 - Average time to complete all operations	4	256.70	1.00	193.54	0.75
G2 - Average time spent in transition	3	36.61	0.80	45.76	1.00
G3 - Time to reach final state	8	666.70	0.22	594.50	0.20
G4 - Average time spent in congestion	3	150.60	1.00	74.93	0.50
G5 - Average distance travelled	4	47.11	0.94	50.11	1.00
<b>GEOMETRIC CRITERIA:</b>					
M1 - Number of WTD used during the scenario	2	24.00	0.89	27.00	1.00
M2 - Number of Hatches used during the scenario	2	31.00	1.00	25.00	0.81
M3 - Number of ladders used during the scenario	2	31.00	1.00	25.00	0.81
M5 - Number of doors used during the scenario	1	78.00	1.00	76.00	0.97
M8 - Number of times FG moved between decks	2	373.00	1.00	322.00	0.86
M13 - Average number of components used per member of FG during the scenario	2	4.47	1.00	4.36	0.98
M14 - Most times a WT door was operated	4	9.00	0.82	11.00	1.00
M15 - Most times a hatch was operated	3	10.00	1.00	7.00	0.70
M16 - Average number of doors used per person	3	1.59	0.82	1.94	1.00
M17 - Average number of WT doors per person	3	1.46	1.00	1.19	0.82
M18 - Average number of hatches used	3	0.27	1.00	0.23	0.83

Table 4.4.4 - PM results for BL-HR and VR<sub>1</sub>-HR, for FG<sub>1</sub> in ES<sub>3</sub>.

For VR<sub>1</sub>-HR, the overall average time spent in congestion (as measured by G<sub>4</sub>) was some 50% less than in BL-HR. This significant reduction in congestion results in VR<sub>1</sub>-HR being able to complete the scenario 11% quicker than BL-HR (as measured by G<sub>3</sub>). While both vessels easily satisfy the international set evacuation time requirements (as measured by G<sub>3</sub>) the levels of congestion experienced exceed the international set limits in four locations (as measured by C<sub>1</sub>) and BL-HR experiences the most severe congestion (as measured by C<sub>2</sub>). As the values for C<sub>1</sub> and C<sub>2</sub> are higher than the regulatory limits, neither vessel would be deemed to be acceptable. To address this issue and to improve the

overall performance of BL-HR, further investigation would be required to uncover the causes of the severe congestion. Figure 4.4.4 shows three of the severely congested regions on board the single passageway BL-HR design during the Action Stations Evacuation ES. It can also be seen how the areas of severe congestion lie at the base of ladders.

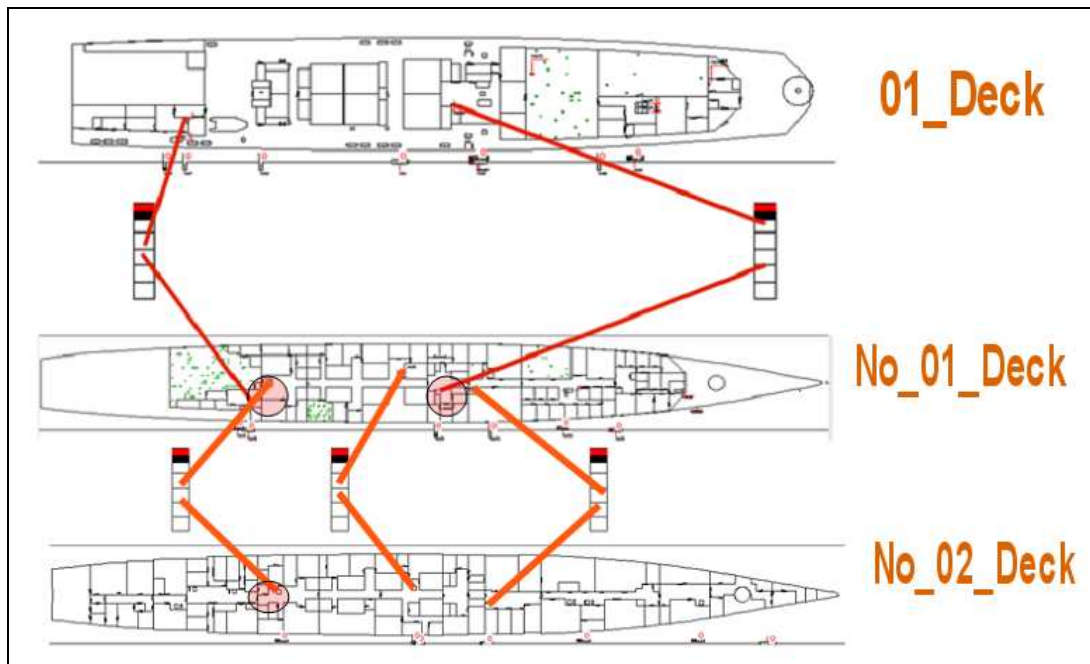


Figure 4.4.4 - Areas of severe congestion during Actions Stations Evacuation for Design BL-HR.

Exploring the areas of congestion in BL-HR (using the population density map: a graphical function available in maritimeEXODUS) suggested that a single additional ladder connecting 01 Deck with No. 1 Deck between two of the severe congestion regions may alleviate some of the congestion by providing an additional means of vertical movement. With this modification in place the HPMx was re-evaluated for the modified VR<sub>1</sub>-HR. The modified VR<sub>1</sub>-HR design now outperforms the BL-HR in each scenario and produces an overall VP which is 6% more efficient than the BL-HR design (see Table 4.4.5) and 8% more efficient than the VR<sub>1</sub>-HR design.



Evaluation scenario	Scenario Weight	BL	VR <sub>1</sub>	% difference between BL-HR and VR <sub>1</sub> -HR
Normal Day Cruising A	1.0	47.81	46.59	-2.61%
Normal Day Cruising B	1.0	51.62	44.98	-14.76%
Action Stations Evacuation	1.0	52.78	44.68	-18.11%
State 1 Preps	1.5	75.95	73.43	-3.43%
Blanket Search	1.5	86.25	85.45	-0.94%
Family Day A	1.5	52.28	49.55	-5.52%
Family Day B	1.5	57.57	53.57	-7.48%
Overall performance of design (VP)		560.29	529.24	

Table 4.4.5 - Scenario scores for BL-HR and VR<sub>1</sub>-HR.

Further analysis revealed that this simple modification eliminated two of the four congestion regions in the ‘Action Stations Evacuation’ scenario, as seen by  $C_1$  in Table 4.4.4 and reiterated in Figure 4.4.4. This results in the average level of congestion experienced ( $C_4$ ) falling by 30% and the average time for each crew member to complete their assigned tasks decreasing by 40 seconds. The change in routes taken due to the additional ladder meant that less watertight doors were used on average by the crew, as shown by a 22% decrease in the value for  $M_{17}$ .

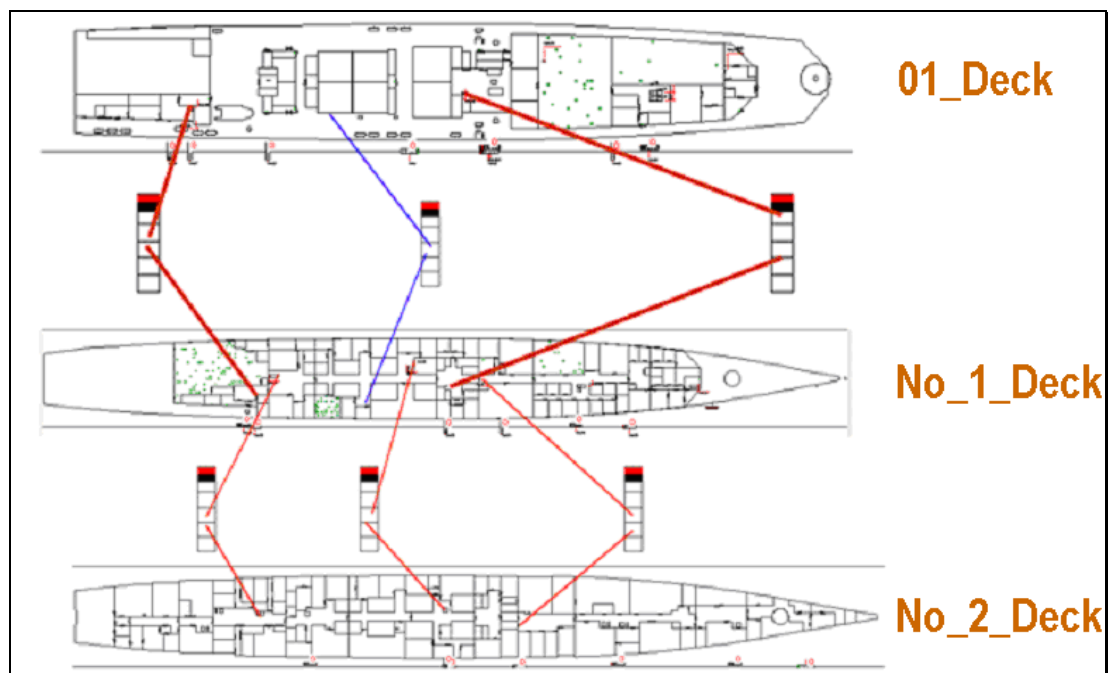


Figure 4.4.5 - Areas of severe congestion after additional ladder implemented in Design BL-HR.

#### **4.4.5 Results of investigations into Design Variants (Low Res.)**

This sub-section presents the results of the investigations on the medium and low resolution models of the BL and VR<sub>1</sub> designs variants of the Type 22 Batch III Frigate design. The performance of these designs was investigated using the approach and followed for the high resolution models. The medium resolution (MR) and the low resolution (LR) models, respectively indicated with BL-MR and VR<sub>1</sub>-MR, were intended to represent vessel designs at earlier stages of the design cycle, therefore the models included less detail than the high resolution models described in the previous section.

Since there was much less detail in the models, it seemed not appropriate to simulate the blanket search scenario. Furthermore, some of the Performance Measures used in the analysis of the high resolution designs, such as the number of doors used, could provide misleading information in the analysis of the Medium and Low resolution designs. This is due to there being far fewer doors in fewer spaces in the lower resolution designs. As a result, the HF analysis performed on these lower resolution designs was identical to that of the high resolution design with the exception that the blanket search ES and the PM relating to standard non watertight doors were excluded from the analysis.

##### **Medium Resolution Model Results**

After performing all the required simulations for each Evaluation Scenario (ES), the respective HPMx were populated for each of the Medium design variants. The results of the human factors analysis (summarised in Table 4.4.6) suggests that BL-MR outperformed VR<sub>1</sub>-MR by 9% , with BL-MR producing an overall vessel performance score of 361.4 and VR<sub>1</sub>-MR a score of 394.2. As such the BL-MR design would be considered the ‘better’ design. Furthermore, Table 4.4.6 illustrates

how the ‘Action Stations Evacuation’ ES is the BL-MR’s worst performing ES, with the ‘State 1 Preps’ ES being its best performing ES.

<b>Evaluation scenario</b>	<b>Scenario Weight</b>	<b>BL</b>	<b>VR<sub>1</sub></b>	<b>% difference between BL-MR and VR<sub>1</sub>-MR</b>
<b>Normal Day Cruising A</b>	1.0	36.12	42.17	-16.7%
<b>Normal Day Cruising B</b>	1.0	47.54	44.70	6.0%
<b>Action Stations Evacuation</b>	1.0	46.74	43.73	6.4%
<b>State 1 Preps</b>	1.5	60.06	74.59	-24.2%
<b>Family Day A</b>	1.5	43.06	49.57	-15.1%
<b>Family Day B</b>	1.5	50.90	51.54	-1.3%
<b>Overall performance of design (VP)</b>		361.40	394.20	

Table 4.4.6 - Scenario scores for BL-MR and VR<sub>1</sub>-MR.

While different numerical values were produced for each of the performance measures and for each of the ES, similar overall conclusions were produced for the medium resolution designs as for the high resolution designs. However, in the medium resolution designs, the performance of the BL design relative to the VR<sub>1</sub> design is significantly enhanced.

After a more in depth examination of the HPMx, it was noted that the level of congestion experienced by the crew in the BL-MR design was a major contributor to reducing its performance. As with the high resolution designs, it was found that the addition of a ladder - in the same location as for the high resolution design - removed much of the congestion and significantly improved the vessel’s performance index (VP).

### **Low Resolution Model Results**

The human factors analysis was repeated for the low resolution designs. As a result of these simulations, the HPMx produced showed that BL-LR marginally outperformed VR<sub>1</sub>-LR by 0.7%, with BL-LR producing an overall vessel performance score of 370.3 and VR<sub>1</sub>-LR a score of 373.0 (see Table 4.4.7).

<b>Evaluation scenario</b>	<b>Scenario Weight</b>	<b>BL</b>	<b>VR<sub>1</sub></b>	<b>% difference between BL-LR and VR<sub>1</sub>-LR</b>
<b>Normal Day Cruising A</b>	1.0	38.75	43.55	-12.4%
<b>Normal Day Cruising B</b>	1.0	46.19	45.61	1.3%
<b>Action Stations Evacuation</b>	1.0	45.93	40.80	11.2%
<b>State 1 Preps</b>	1.5	66.79	71.18	-6.6%
<b>Family Day A</b>	1.5	42.28	36.07	14.7%
<b>Family Day B</b>	1.5	50.57	54.80	-8.4%
<b>Overall performance of design (VP)</b>		370.30	373.00	

Table 4.4.7 - Scenario scores for BL-LR and VR<sub>1</sub>-LR.

Furthermore, ‘Family Day B’ is BL-LR’s worst performing ES, as opposed to ‘Action Stations Evacuation’ ES in the High and Medium resolution designs, and its best performing ES was ‘Normal Day Cruising A’, as opposed to ‘State 1 Prep’ in the high and medium resolution designs.

While the low and high resolution designs produce the same conclusion concerning the overall relative vessel performance, the best and worst scenarios suggested by the low and high resolution designs were different. The level of difference between BL and VR<sub>1</sub> for high, medium and low resolution designs was considerably different.

### **Discussion of HF analysis using Lower Resolution designs**

Adding/removing details to the vessel design significantly impacts the overall HF performance of the vessel and may mask features of HF performance in the final (high resolution) in-service design. Thus the HF performance derived for a low resolution design will not be the same as the HF performance of the high resolution version of the same overall design. However, when comparing similar resolution designs of competing variants (or design iterations of a given design),

the HPM approach is useful in identifying potentially superior HF performance in competing designs.

Thus in the early stages of the ship design process, the HPM technique could be useful in determining whether design iterations (or competing design options) have improved or degraded HF performance. However, given that in the very early stages of design, much of the infrastructure which will impact HF performance is not present, it may not be efficient to invest considerable effort in attempts to optimise HF performance.

It is suggested that the set of ES and PM presented could be used to evaluate the high resolution design variants, however they may not be appropriate for evaluating low resolution variants. Indeed, the ES used in the analysis of high resolution designs may need to be simplified by maintaining their essential features but reflecting the lower resolution of the designs. Identifying and testing a set of ES and PM appropriate for low resolution designs would be the subject of further research, ideally undertaken in collaboration with potential end users.

### **Summary**

The HPM was used to identify which of two competing vessel designs produced the best overall HF performance, thus the HPM methodology is *discriminating*. The HPM was also used to identify areas in which the HF performance of the winning design variant could be improved, thus the HPM methodology is *diagnostic*. Furthermore the HPM can routinely be applied to any given design and so is *systematic*, the process by which the decisions are made are *transparent* and another engineer using the methodology would arrive at the same conclusions and so the methodology is considered to be *repeatable*. Furthermore, the HPM

technique has been demonstrated to be able to discriminate between competing low resolution design variants. However, it is suggested that when evaluating low resolution designs, it may be necessary to make use of a different set of evaluating scenarios and Performance Measures to those used in the evaluation of high resolution designs.

## **5 - Discussion**

This chapter discusses the major issues raised by the research presented. The relevant issues cover the wider design related implications for the practice of complex ship design. This discussion does not consider all the aspects associated with the integration of personnel movement simulation into preliminary ship design, nor considers the application of such an integration into the preliminary design of all types of ships; rather it focuses on the implications of the solutions developed instead of the technical issues addressed during the execution of the research and presented in Chapter 3. These implications and some more detailed issues considered in this section are divided into those relevant to the integration approach (see Section 5.1) and to the design process implications (see Section 5.2) and so are discussed separately, even though there may be some areas of overlap. The next chapter reviews how the aims of the research have been met and draws on the conclusions to indicate possible future research which would develop the research presented here.

### **5.1 Design approach**

This section considers the development to integrate in preliminary ship design, the Design Building Block approach and the simulation of personnel movement in escape and evacuation (emergency) and ship operations (non-emergency).

#### **5.1.1 New way of progressing towards a design solution**

A new way of undertaking preliminary ship design was investigated. The research demonstrates it is possible to undertake personnel movement simulation and integrate it into early design. This allows the designer to perform a considerable number of personnel movement simulations when the design is still evolving and

opens up the possibility of changing the way in which the designer progresses a design. This means that the designer is not just informed on operability and evacuation related design features early on in the design process, but also on other relevant issues which can then inform design choices, such as the crew organisational structure and operating procedures.

The work presented in the previous chapters addressed the question as to whether aspects relevant to the design process, such as crew organisational structure and operating procedures, should be considered by the design team as design variables. That is to say, whether designers should just physically design the ship, or if they should take into account, as part of the design task, additional aspects such as working procedures and/or the hierarchical organisation of the complement. When considering the wider design environment, there are approaches and innovations, such as simulating personnel movement, general simulation based design (see Section 2.3) and elements of concurrent engineering (such as through life cost implications), which have been proposed to be considered early in design, with the expectation they would modify the way in which ships are designed, and, improve the quality of the final product. This research has shown that it is possible to integrate personnel movement simulation in early stage ship design and the benefits that can derive from following such an approach. Therefore, all the elements (i.e. data and information) that are required to define and set up the simulations (i.e. minimum detail necessary to personnel movement, scenarios, and operations - see Section 3.5) could now be considered part of the set of main design parameters to be addressed by ship designers.



The wider use of simulation in ship design (e.g. simulation of dynamic stability, damaged stability, underwater sound emissions and radar cross signature) has proven to be beneficial as it allows, for example, virtual prototyping, performing virtual tests and trials and analysing a design in a controlled environment in which performance can be tested, measured and monitored in a non-intrusive manner. Assessing a design's (simulated) performance and analysing the feedback received from a specific software program are, in general, interdependent components of simulation based design techniques. Probably one of the most beneficial features of computer simulation software programs is their ability to provide a bijective<sup>27</sup> type of feedback i.e. where for every designers' "action" that modifies the design under consideration there is a corresponding "reaction" captured by the software and presented as feedback [Bill, 1999]. Feedback from a series of simulation runs could provide designers with positive reinforcement, give cause and effect experience, promote recall of prior knowledge and provide assessment information relevant to task performance.

Novel insights into the nature of architectural design problems and new ways of progressing towards a design solution can be derived from simulations. Computer simulation transforms interrogating an evolving design from a mental construct into a numerical one. This requires the translation of assumptions that may go unnoticed and unappreciated in an implicit design process into explicit conditional statements (i.e. formalised algorithms). The risk of not taking into account important assumptions can be considerably reduced by defining causal<sup>28</sup> relations between

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<sup>27</sup> In mathematics, a bijection, or a bijective function, is a function  $f$  from a set  $X$  to a set  $Y$  with the property that, for every element  $y$  in set  $Y$ , there is exactly one and only one element  $x$  in set  $X$  such that  $f(x) = y$  (<http://en.wikipedia.org/wiki/Bijection>).

<sup>28</sup> Causality is the relationship between an event (the cause) and a second event (the effect), where the second event is understood as a consequence of the first (<http://en.wikipedia.org/wiki/Causality>).

operations and, in the research, the problem of associating design intentions (cause) with design manifestations (effect) was addressed in the domain of personnel movement simulation. It is complex to address the issue of identifying and formalising these assumptions and of similar complexity are their analysis, discretisation and translation in computer code. This is because there are numerous relational decisions which are generally implied and assumed in the designer's mental construct of the design. The process of developing the interface software to interface the ship design and personnel movement programs, inevitably led to clarifying these assumptions and incorporate them into software code (Appendix E).

Setting up a digital simulation and integrating it in the early stages of design requires aspects of a design problem to be abstracted into mathematical terms that can be executed through logic-based methods (i.e. translated into algorithms and code executable on a computer). Therefore, simulations can be thought of as closed-loop, dynamic, rule-based applications created by encoding multiple discrete conditional procedures (input) which are employed recursively and in a combinatorial manner, resulting in a single system's behaviour (output). While such systems are by definition deterministic, they are often considered "unpredictable" because the number of conditional rules they contain can create a vast number of possible rule combinations, which greatly reduce the observable predictability of the system [Lobel, 2007]. In addition, such systems (the more evolved ones) can be based, for example, on neural algorithms, non-linear dynamic rules or fuzzy logic, hence are completely deterministic but completely unpredictable, because their behaviour is very sensitive to initial conditions [Bates and Carnevale, 1993]. Thus simulations can provide a method for the dynamic evaluation of a given rule set associated with the design under examination.

Designing without an integrated use of simulation means that designers can ignore the existence of some rules (when these rules are implicit in the designers' assumptions and mental construct) or use simulation as either a method of visualisation or as a source of feedback (i.e. as an assessment tool) focused on specific aspects the design performance. However, when simulation is integrated into the design process (as proposed in this thesis), the logic programmed and embedded in the software tools used cannot violate the conditional statements upon which such logic was formed (i.e. hypothesis, assumptions and sequence of computational instructions). This inviolability of the conditional statements implemented in a computer program renders the proposed integration of computer based simulation (and, in particular, of personnel movement simulation) into the design process a valuable method for the analysis and exploration of design intent, solutions and performance.

Other aspects, for which simulation is seen to be beneficial in ship design, include the fact that it can help to highlight which are the particularly advantageous aspects of a given design solution and can support the demonstration of the performance of novel characteristics introduced in a design solution. There can also be additional merits in the concept of a performance based design [Famme et al., 2009] for when the three dimensions of CAD are enhanced by a fourth dimension, that of performance simulation. For example, general simulation of Hull, Mechanical, Electrical & Damage Control (HMEDC) systems can be used to verify and validate ship systems' performance in real-time during all design phases. It is when this fourth design dimension (that of simulation) is integrated into the design process (as opposed to being used as a stand-alone verification and validation assessment) that the benefits to the designer can be even greater.

In this context, integration is intended as the harmonised combination of previously separated procedural and technical considerations in a unified process in which designers can increase their confidence in the evolving design. Such integration enables the exploration of the design space in a rapid and easy way: rapid, since the necessary tools are seamlessly compatible and included in the same interface; easy, since it does require limited additional effort or training to be used and its results are immediately applicable to inform the design process. Thus, the information supplied by the simulations could aid designers in making more informed decisions and so contributing to de-risking the emergent design and increasing the designers' awareness and understanding of the performance of the solution(s) being investigated.

The benefits of integrating simulation early on in the design process are seen to be further enhanced since the design is still fluid and, thus, time and resources ought to be available for implementing necessary modifications and/or exploring alternative design solutions. In addition, the early integration of simulation into the design process can help designers in systematically increasing their knowledge acquired as part of the design process and capturing it for future uses.

As mentioned, simulation enables the designer to gain increased awareness of the design, to have better confidence in the solution under examination and, ultimately, to make more informed decisions. Given the advantages offered by simulation techniques, if these are performed at the front end of the design process and assuming they provide insights into how the design stands in relation to the requirements that initiated the process, then, the subsequent process to improve the design, ought to be facilitated. Whether this will also speed up the whole

design process will be highly dependent on a wide variety of other aspects to be considered in a specific design. Nevertheless, it is to be expected that the use of information gathered from simulations conducted early on in the design evolution will contribute to reducing the risk of non-compliance of the final solution with the initial requirements; this is because it should assist in revealing potential rework which would then be avoided in the more costly downstream phases (e.g. detailed design for production, production and in-service).

Ultimately, a design process can be seen to be not just one of problem solving, but one of problem setting. This emphasizes the design question over the design solution i.e. the setting of the design problem as opposed to presuming that the design is simply a formal outcome. Attention was drawn to the methods for abstracting, encoding and analysing conceptual assumptions and procedures in structured, conditional and logical formats. The encoding process of writing a simulation embodies the critical moment during which intuition must take the form of logical and/or Boolean conditions to be tested in a virtual space. This process considers attributes of the system as an opportunity for reflection and interrogation and constitutes an integral part of the proposed way of progressing towards a design solution.

The proposed approach for integrating simulation into the design process also involves the simulated results being analysed and interpreted to derive meaning. The analysis and interpretation of these results and the understanding of possible cause-effect correlations mean designers should carefully consider the way they choose to approach design problems given that simulation should provide a tool for enhanced understanding, analysing, and critiquing the design concept.

Integrating simulation in the design process is likely to reveal many basic assumptions and provides a mechanism by which those assumptions may be interrogated. This process could result in the potential for truly novel design solutions being developed. However, there is the danger that the designer may be biased towards tuning the design concept and specific features (e.g. layout and ship operating procedures) to obtain the best results with regard to the simulation undertaken, rather than necessarily improved overall design solution(s).

### **5.1.2 The advantages of conducting PMS in early design stages**

The integration of personnel movement simulation (PMS) expands the scope of preliminary ship design by including personnel related issues (i.e. organisational and operational) in the aspects to be considered by the preliminary ship designer. The simulation of personnel movement, however, does not include all the aspects associated with personnel issues relevant in ship design. Thus, there are some aspects that cannot be readily modelled mathematically (e.g. knowledge of the ship layout, prior experience, intuition, initiative, emotional state, etc.). Consequently, not all aspects associated with the determination and functioning of ship's complement can be computed by personnel movement simulation software.

In addition, in selecting a ship's style and designing the layout of a ship, there are choices which depend on wider operational issues (e.g. whether to place the Operations Room close to the bridge or to the Main Communication Office) that are determined by considerations other than those of proximity and accessibility (i.e. not determined by personnel movement performance). Therefore, even if it was possible, the effectiveness of such confidential choices should not be solely evaluated by assessing the simulated performance

of onboard personnel evolutions, but by evaluating the impact of considerations of other concerns, such as those of safety, survivability and security.

However, even if some personnel related issues might not be accurately dealt with by just considering simulated personnel movement performance, the method proposed is considered to have the potential of contributing towards a more holistic approach to investigating the design and supporting the designer in more rapidly converging to a design solution. This is because the analysis of the crew's performance can be based on the assessment of a predetermined number of alternative possibilities (design choices), which are obtained from considering design decisions made on the basis of safety, survivability and security.

A more holistic approach to design synthesis could be achieved if the proposed method for integrating PMS in the design process is applied in the early stages of the process rather than simulation being undertaken just in detailed design stages. Rather it is at the very front of the design process that the design is primarily being determined and when the designer can explore the design solution space and will be making the main decisions on the configuration of the eventual solution. At this stage, designers are not just selecting between different design options, but should also be using their creativity, knowledge and experience to conceive alternative design solutions to meet the technical, performance and operational needs being elucidated in preliminary design.

The approach proposed can support the decision making process and allow the designer to make more informed decisions than traditionally have been possible by drawing on those derived from the personnel simulation output. This information could affect, not only stylistic decisions, for example, on the layout

of the ship, but also decisions on procedural, organisational and operational aspects of the ship's complement, for example, manning numbers and roles assigned to the members of the crew.

It could be argued that this approach could make the initial design process more complex, since more work would be required at the front end and the additional detail (resulting from having to configure the design for personnel simulations and from the relevant output) could overload the designer and complicate the design exploration. However, as shown in Section 3.8, adding extra detail to the model is a relatively straightforward operation. In addition, as shown in Section 3.8, the analysis of the results of such simulations can be rendered intuitive with the use of the developed visualisation tools. Therefore, if on the one hand the proposed integration can be seen as an extra workload for the designer, it can also be considered as an operation which adds relatively little further complication to the early stage design process which brings into it the benefits of conducting PMS in the crucial phase of the design process.

Getting the HF input at a stage when it can still influence major configurational choices, rather than left to later phases, means there is also scope to significantly influence the process of converging to a design solution in terms of complement and its organisation. The approach is considered to also bring to the fore end of the design process some very important issues and potentially new design drivers. It enables the designer to design the ship together with its complement (in terms of skills, organisation and numbers). This then gives the designer greater confidence that the ship matches the performance and operational requirements it was originally conceived to meet.



The proposed approach not only could be seen as a way of de-risking the design by highlighting early some of the likely significant issues, but it could also enhance the design of ships without adding redundant technical complications (i.e. additional designer effort) and without limiting the need for flexibility in early stages of the design process.

The research has focused on showing an example of how to integrate personnel movement simulation in the early stages of ship design and, within its scope, is considered to have identified that it is possible to achieve this without unnecessarily overcomplicating the process or reducing the flexibility necessary in early stages of the design. From this approach to the integration of PMS and PSD, it has been possible to draw some general conclusions related to the integration of personnel simulation into early ship design and some very specific ones associated with personnel movement simulation (e.g. the required level of detail in model description - see Section 3.7 - and the connectivity items definitions - see Appendix C).

To cover the main issues of the numerous aspects of personnel impact on the ship (i.e. aspects of a holistic approach to designing ship and personnel together), other issues like survivability and safety need to be considered. However, these aspects were beyond the intended scope of the current research and, consequently, the proposed approach does not cover all the issues related to personnel, nor it covers all aspects of personnel movement which could be considered when designing ships.

As mentioned at the beginning of this sub-section, modern technology does not allow all aspects associated with the ship's complement to be translated into mathematical functions and algorithms. This means that certain aspects of human behaviour cannot be modelled (and therefore simulated) in a digital environment. These limitations, however, do not affect the proposed method to integrate personnel movement into preliminary ship design, nor do they challenge the conclusions drawn. The research has shown it is possible to integrate movement simulation into early stage ship design. It has been argued that this integration should take place early in the design process and could be used to de-risk the design and increase the designer's confidence in the emergent solution.

Integrating personnel movement simulation into early stage design should enable the designer to obtain a better feel for those HF aspects that are important in determining the overall design although such aspects have not previously been formally addressed at this stage. Section 6.3 addresses those general design issues arising from the integration of personnel movement simulation in preliminary ship design that might require further investigation. The research identified and addressed an area of preliminary ship design that has not been properly addressed. Perhaps all the issues related to PMS identified in this work will need to be considered in the future and, in order to overcome them; a new strategy to approach and conduct preliminary ship design might be required. What appears to be clear is that the early design personnel movement simulation addressed is a different kind of simulation from any other type of PMS and it was used in a different way (see Section 5.1.3).

### 5.1.3 A different kind of simulation used in a different way

When personnel movement simulation is conducted in preliminary ship design it is substantially different from that performed later in the design process since the need for later simulations is to demonstrate compliance with rules and regulations or finding a solution to a specific problem (i.e. remedial use). Later in the design process, the ship design definition is less easily reworked than that being developed in the early stages of design, it is also very much more detailed which means it is possible to obtain far more realistic and accurate results from simulations undertaking.

The simulation investigated in this research can be considered of a different kind and performed for a different reason to other personnel movement simulations. Firstly, it allows the designer to define all the initial details, conditions and parameters of the simulation (e.g. complement, procedures, environment, operations and scenarios - as described in Appendix E), whereas commercially available software for personnel movement simulation only allows certain aspects of a simulation to be defined by the user. Secondly, the personnel movement simulation has been performed in early stage design and so can be seen as a different kind of simulation from that conducted later on in the design process. The main difference lies in the intention behind obtaining the simulations output given early stage design PMS is not performed to provide very precise results (i.e. close to reality), but at gaining an insight into the design performance. Unlike downstream use of PMS, precise accuracy of the output data is not the intent, but rather it is the need to identify major problems and inform broader design choices with regards to personnel movement aspects.

The use of the PMS described in this thesis differs from many equivalent simulation software packages available in the market. In general, these PMS tools only take into account certain aspects of personnel movement (i.e. evacuation, crowding or general flow) and are used to verify compliance with specific standards, rules and regulations. Conversely, the PMS developed in this research is used as an integral step in the preliminary design process and as a tool to assess and improve the initial design by informing designers in a direct and intuitive manner about the general consequences of their early decisions. In summary, the main difference between the use of the simulation considered here and that of other PMS is that it is used not only as a method of visualization or assessment, but also as a tool for interrogation and exploration of early stage design alternatives.

Rather this early stage use of simulation allows the designer to be made aware of the whole-ship usability issue (i.e. large scale operability, see Section 2.2) and can then be used to inform the design evolution. This has not been addressed traditionally due to the lack of appropriate approaches and tools able to interface with this type of simulation and therefore limiting the early stage analysis to traditional quantitative topics such as stability and powering.

In design practice, consideration of personnel movement through the ship design was addressed much later and at a relatively subjective level, when it was too late to make a real difference in the design style being adopted. This is because by that stage the design, firstly, is largely determined therefore the scope is limited and, secondly, is constrained by its detailed definition making it unattractive to implement changes due to the complexity of introducing any major modification. Also, by this stage, the context in which the design team is operating has changed

from that of early stages design. Once the overall design is fixed the design team is under considerable pressure to deliver a definition for approval by customers and classification society and then a detailed definition for manufacturing. This means that time and resources available for implementing any modification are quite limited. This constitutes another reason why ideally personnel movement simulation should be performed early on in the design process, since the design is still fluid and more time should be available to investigate and experiment alternative design solutions by investigating more design options.

The use of simulation in preliminary ship design as opposed to its use downstream in the design process, is related to its objective: informing the designer and the end customer. The objective of the type of personnel movement simulation considered in the research reported in this thesis is to give the designer a sense of confidence with regard to an important aspect of design that has not been possible to address previously. The approach demonstrated allows the designer to have important insights and make more informed decisions as to whether the configuration, still in its very early stages, needs to be modified to take into account manning issues in order to avoid the problems revealed by the personnel movement simulation.

The possibility of using operability studies on early stage design models opens up further advantages to the designer. This information relevant to the designer at a crucial stage in the design process is revealed at the time when major stylistic decisions are made. For example, from the simulation results, the designer could infer there is no need to have two side passageways but only a central one, or decide whether there is a need for additional vertical access

routes to certain areas of the ship. In preliminary design what concerns the designer is identifying and highlighting if there are any significant problem areas while the design is still malleable. In this respect, the approach proposed is able to provide the designer with a precious and valuable insight into identifying and locating potential problems and the possible causes behind them.

Based on previous experience in ship design and through the current research distinct advantages have been seen in integrating personnel movement simulation early on in the design process. Despite some limitations and practicality issues, which have been described in Chapter 3, this approach has the potential to inform the designer about the performance of the design under investigation. Even if further iterations and investigations of such aspects might be required, the research has shown how this approach can be useful in readily informing the designer and other stakeholders of the performance of the emerging configuration, giving additional confidence in the effectiveness of the design solution. Effectiveness addresses the overall operability of the ship (see Section 2.6) which is achieved through a more informed decision making process in which the simulation results highlight risk areas and can be seen to inform the efficacy of alternative design solutions in resolving those problems. This could lead to achieving a better design, and resulting in a more comprehensive and creative process. In fact, not only could the designer be made more aware and confident of the usability and performance of their design, but are enabled to be more creative by exploring different design solutions (e.g. explore a trimaran configuration for a frigate required to be designed to provide better access to her flight deck).

Despite personnel movement being a question of major importance, it is only one of a set of disparate design issues to be taken into account and should be considered alongside other significant design drivers. Personnel movement simulation is important to address as early as possible in the design process as it can lead to operational and procedural improvements and to the possibility of reducing the complement. With ever greater analytical ability and growing facility of computer based methods, there is a need to find a way of bringing together all the various issues informing design decisions. In this context, the integration of personnel movement simulation into preliminary design of ships constitutes just one aspect of a whole new approach to complex engineering product design.

#### **5.1.4 The proposed approach**

To demonstrate the viability and utility of the proposed approach the research focused on a specific example, that of a Type 22 Batch III Frigate. All the required information was supplied by the UK MoD as described in Section 3.4. The choice of this particular frigate design being an in-service ship enabled comparison of simulation results with actual crew experience and in being a complex ship, both in terms of the range of operations and the ship layout (i.e. large complement and two passing decks). Due the time constraints and technical limitations (e.g. amount of work required to update core algorithms in maritimeEXODUS, as detailed in Section 3.3), the research was not as extensive as originally envisaged. The nature of the EPSRC project and the time and resources available resulted in the exploration of just a limited number of alternative ship configurations, scenarios and design solutions.

The main factors limiting the investigation were:-

- The primary function of the EPSRC funding was to show the feasibility of the proposed approach and analyse the relevance of its results; so work concentrated on a single case study;
- The significant amount of time spent defining what were the relevant issues to analyse and the appropriate scenarios to be investigated;
- Much of the early part of the project was absorbed with the personnel simulation team in the Greenwich FSEG to jointly overcome those technical limitations and constraints in using maritimeEXODUS beyond its use in escape scenario modelling (e.g. DXF issue connected with the automatic node flooding described in Section 3.10) to a much more general approach to personnel movement simulation (i.e. operations and non-emergency scenarios - see Section 2.5);
- The data available (e.g. procedures and W&SB relevant to the Type 22 Batch III - Appendix D) and the necessity to meet the UK MoD requirements, specifically in terms of the limited number and typology of scenarios and configurations that MoD particularly wished to address (i.e. list of scenarios as detailed in Table 2.6.1 at page 45).

From a broader stance than the EPSRC project, it would have been worthwhile to explore a number of additional scenarios, which might have been more significant from the point of view of generating the complement of the ship, such as replenishment at sea and loading/unloading ordnance and general supplies. Other personnel movement intensive scenarios that could have been considered were as significant for initial design insights include NBCD evolution changes of watch and change of ship watertight integrity state (e.g. Condition X to Condition Z).



With regards to the applicability of the proposed approach in preliminary ship design, the question arises as to how early in the design process should this capability be adopted (e.g. in *ab initio* or subsequently in the concept phase). To properly answer this question would require a more extensive investigation, however, it is likely to be highly dependent on the actual design. Thus for a major design (e.g. a new combatant or a capital ship) PMS it would seem such investigation ought to be conducted as part of the concept studies, given that such insight would inform major cost/capability trade-offs.

The approach and tools developed could to facilitate the exchange of information between the various parties involved in the design process. Undertaking personnel movement simulation in an integrated fashion would provide a common working environment (i.e. software platform) could assist in the realisation of concurrent engineering objectives. The software platform, which was developed as a prototype, could constitute digital support to the design decision making process and thus represent a single data exchange environment for integrating personnel movement simulation in the preliminary design of ships. This environment could support and facilitate the design process by giving to all relevant stakeholders involved in preliminary ship design ready access to the same information and data thereby facilitating concurrent engineering.

### **5.1.5 Implications of the research on the approach to PSD**

The research has shown it is now possible to integrate personnel movement simulation in the ship design process from its earliest stages and how this can be beneficial to the designer. It can be seen as a step towards bringing to the initial stages of the ship design process aspects of the design that traditionally

were addressed much later in the process. Furthermore, these personnel related issues can be considered as new design variables, such that personnel procedures (i.e. operations, organisation and scenarios) and complement issues (i.e. W&SB, crew numbers and crew characteristics) can now be included in preliminary design. This might require rethinking how naval architects design ships since it is now possible to take into consideration such aspects from very early stages.

It is possible, for example, to concurrently evolve the design of the ship and its complement, which could include defining personnel characteristics and skill requirements together with the onboard organisation. The approach and tools developed enable the design to run personnel movement simulations as part of concept studies. This could facilitate the early identification of opportunities to reduce the complement and/or achieve a better onboard organisation, giving the designer confidence that the current design has an appropriate balance between configurational and operational aspects.

Reducing the complement or improving procedures and the crew organisational structure could also further improve the overall design. Defining a new configuration of the ship that can then be explored for different crew organisations (e.g. branch structure and management structure) could further enhance a design's effectiveness. Thus one could investigate, early in the design process, whether to have a larger complement of low skilled people (i.e. operational flexibility achieved through people) or a smaller crew of high skilled people employed in conjunction with more automation (i.e. operational flexibility achieved through knowledge and technology). Different skill levels could be simulated by modifying some parameters in the "personnel setup table" (i.e. the physical and personal

characteristics of the simulated crew defined in the “manning table” as described in Appendix E).

Design decisions based on PMS considerations, such as those described above, have implications for life costs and, while the designer could expand the scope of design exploration, stakeholders could make more informed decisions on a potentially wider range of design issues.

## 5.2 Design process implications

This section considers how the developed approach feeds into the design process and the design process implications of including personnel movement simulation considerations at early stage ship design. Three different sets of limitations to the integration of personnel movement simulation in a practical preliminary ship design process (appropriate beyond the current research environment to working design organisations) have been identified:-

- a) The first set relates to the breadboard toolset developed to integrate the simulation tool and the CASD system, as described in Chapter 3. In particular, when compared to a fully working system, this breadboard toolset is limited not only the speed at which case studies could be analysed, but also the range of measures that could be taken into account and actually integrated in the design environment.
- b) The second set arises from the structure and core algorithms of maritimeEXODUS (see Section 3.3). These restrict the extent and range of evolutions that could be simulated (e.g. all simulations involving movement of injured personnel and transfer of equipment/ammunition are excluded), as well as the data that could be extracted from the simulations and presented to the designer

(for example, data on distances travelled, number of instructions received and time spent idle).

c) The third set relates to the contrast between maritimeEXODUS' need for very accurate input data and the level of numerical information available in preliminary ship design. This is probably the most significant limitation since it depends on the very nature of both personnel movement simulation (large volumes of very detailed and accurate data) and early stages design (high level information and a more fluid definition) and, as such, cannot be easily overcome by technical solutions. To further investigate the latter set of limitations, a sensitivity study was performed with the specific aim of exploring the issue of the balance between complexity versus accuracy.

### **5.2.1 Sensitivity analysis**

The objective of the sensitivity analysis, presented in this sub-section, was to identify the stage of the design definition when it is appropriate to consider the results of personnel movement simulation and investigate alternative configurations. Important results were identified, but, given the limitations described in Section 3.5 and 3.7, it has not been possible to complete the analysis to the extent originally envisaged and, therefore, to quantify their influence with the desired precision. Table 5.2.1 indicates in broad percentage terms the relativities of different levels of definition included in the model description and the implications in terms of simulation results compared to reality (i.e. complexity versus accuracy). The order in which the table is arranged derives from the experience of using the approach; the percentage values in the

table are indicative and serve to show the broad relativities between the different aspects considered.

Level of detail	Designer additional input/effort	Description of the reduction in detail level	Comments on results and overall delta with reality (influence of a single decision)
100%	100%	“As build” level of detail (as from General Arrangements provided by the MoD)	Simulation results show good compliance with reality. ~ 5%
90%	95%	Only one type of horizontal connectivity items	In very few occasions this change makes a noticeable difference. ~10%
80%	70%	Horizontal connectivity items positioned “automatically” in an arbitrary position (half of the length of a compartment or passageway interface)	This operation has very little impact on the results given the level of definition of the model description. ~ 10%
70%	60%	Vertical connectivity items, type and position automatically implemented.	Unrealistic results. This operation will have to be done manually, but there are very few such items in a model therefore the operation is very easy to perform manually. Non viable.
65%	65%	Position of equipment items changed	This operation has to be performed manually, but shifting eq. items is limited and has very little impact. ~ 10%
55%	50%	W&SB and information about the complement characteristics reduced and simplified	A simplified set of parameters allows speeding up this task and maintaining a logical flow of information. ~ 15%
50%	45%	Scenarios and procedure definitions simplified, without changing the underlying scope	The scope for further reducing this task is limited. A simplification of the definitions allowed to reduce the time needed to populate scenarios. ~ 20%

Table 5.2.1 - Broad percentages indicating the relativities between the level of design definition and the resultant implications in the simulation results compared to a general perception of reality (i.e. complexity vs. accuracy)

Absolute values of simulation outputs cannot be highly accurate in preliminary ship design stages, rather the difference between the same set of simulations, run on two different designs, can be seen to representative of reality and provides a good indication to the designer as to what are the implications of particular design choices. Integrating personnel movement simulation in preliminary ship design can therefore be used to perform incremental studies to provide a better understanding of where the performance of different design solutions differ and how to evolve the design rather than in having a quantitatively accurate assessment of a single design itself. To this end, an indication of relative level of importance of different performance measures is more relevant than absolute values and so

provides useful information to progress the design by assisting in the making of informed decisions.

Values obtained from simulation output can also be used to evaluate the performance of a design model against data derived from reality and, according to the investigation conducted by the Greenwich FSEG [Galea, 2000], these results appear to be reasonably close to those obtained from physical simulations. To put this into context, at the concept design stage, the baseline ship design and its associated overall cost have typically a “measure of uncertainty” which is considered by naval ship concept practitioners to be up to 20%, although this is virtually impossible to prove [Andrews, 2008]. Any simulation analysis used in concept or early stage ship design should be able to provide a sufficiently comprehensive and realistic indication of the ship performance for personnel movement evolutions with an equivalent level of accuracy.

### **5.2.2 Procedural implications**

From a procedural perspective, the integration of simulation with the interactive design process can follow either of two approaches parallel and serial (as described in Section 3.6). An objective of the research was to investigate how to best iterate a design and converge on a solution, following either of the two approaches or a combination of both.

From the experience gained in using the approach and tools, it was concluded that, in early design stages, the results obtained from personnel movement simulation are more appropriate if used to compare and contrast different design solutions. Absolute values from simulation output can be inaccurate therefore less reliable and usable, while the relative difference (i.e. the difference in performance data)

between the results obtained from comparing solutions, would give the designer a realistic indication of the better solution against the key performance indicators (KPIs) identified for that specific design under investigation. The incremental value of the KPIs obtained from the simulations can also give believable indications of the trends in important aspects of the design, such as cost and general performance. Incremental studies should enable the designer to identify where there might be aspects of the design likely to lead to problems downstream in the design evolution, what might be significant cost drivers and what are the main performance issues associated with relevant design decisions.

Such issues can then be addressed early in the design process facilitating the exploration, investigation and understanding of the characteristics of the design space with respect to personnel interaction with the onboard environment. Although, ships should have been designed in conjunction with the determination of the crew's skills mix required to operate the ship, this has not been feasible to date and so ship designers have inevitably focused on other crucial aspects, such as powering and stability.

Traditionally, flexibility in the operation of a ship has been achieved largely through the use of well trained and experienced people adapting to the ship to carry out tasks not spelt out or even perceived when the design was produced. However, ships now need to be designed for a more demanding context: there are less people on board and, as the people are more specialised and trained, as the education levels of the crew increases and as the jobs they are called to perform are more crucial, the whole issue of the people skills versus more sophisticated equipment and the environment in which the ship is to operate has

become more important. This wider issue can now be tackled alongside other personnel issues, such as retaining good personnel, reflecting the living standards of the population from which the crew has been provided.

### **5.2.3 Usability and practicality**

The scope of the research was limited by existing capabilities in both main software packages, for conducting a new type of analysis and integrating it with preliminary ship design. The main challenge was, therefore, to integrate and use two existing and separate software packages to perform a new type of analysis. Some additional design capabilities were introduced to allow simulations to be performed in a design environment, but the interface software produced does the vast majority of this work (see Appendix E).

The identification and specification of these new capabilities (e.g. connectivity items definition and use, see Appendix C) was performed by the candidate, while their implementation in maritimeEXODUS was done by the FSEG, as owners and developers of the simulation software. Even if all these limitations restricted the use of the developed system in many respects (e.g. speed, user interface, visualisation of results), it is relevant that the interface software was never meant to be delivered as a finalised product, but rather as a working breadboard system to achieve and demonstrate the research aims in line with the EPSRC funding principles.

Discussion on usability and practicality of the solutions developed highlights the differences in the logic used to represent and model the design in the two component software packages and how Operational, Procedural and Geometrical information can be transferred between the two main software programs (see



Section 3.8). Part of this practicability is linked to the software capabilities (as detailed in integration issues - see Section 3.5). The development of the ship design approach and relevant procedure was tightly coupled to the software tools developed. In addition to the specification and implementation of the required software's capability enhancement and integration, the UCL team defined the key performance measures considered relevant to the designer with regard to personnel movement and how they could be presented to directly inform the ship designer.

#### **5.2.4 Software integration and automation**

The level of software integration and automation achieved in the research facilitated the investigation of aspects related to personnel movement in early stage ship design. The early stage definition of the design, together with the need to retain flexibility for design explorations and trade off investigations, was balanced with the level of definition required to allow evaluating operability from the simulation of personnel movement. The automatic generation of some definitions was included in the design model prior to analyses to ease this problem (e.g. automated placement of connectivity items - see Section 3.6). The level of detail required to conduct personnel movement simulation could be seen to still be high, but there is felt to be scope to automate the process of inserting such details in the design model. Thus, the details required by maritimeEXODUS could simplify the design activity, reduce the workload on the designer and could also avoid potential inconsistencies and errors from manual input. The designer could then focus on the main design activities, while the software could take care of the repetitive task of generating the necessary detail and providing the necessary accuracy of the elements introduced in the design model.

Inserting such details in the design model in an automated fashion (in particular, horizontal and vertical connectivity items - see Section 3.7), could also diminish the additional effort which might inhibit the need for flexibility necessary in early stage ship design. Flexibility could be maintained in two ways: either by removing all details relevant to running personnel movement simulation when undertaking general early design explorations and then updating the design and automatically re-inserting the details to undertake further PMS; or by modifying the design (without removing the details) and verifying that all connectivity items are coherently connected with the Design Building Blocks. It is considered that the latter could be automated given that it just requires determining whether the network of connections between all the Design Building Blocks (i.e. the network of possible routes the simulated crew can use) is still valid and, therefore, appropriate for performing the simulation. It is considered that this is a relatively simple problem to solve in computational terms as it would be sufficient, for example, to check whether the number of compartments in the network of connections is equal to that of the Design Building Blocks used in the design model.

### **5.2.5 Presentation and visualisation of simulation results**

As described in Section 3.9, a range of methods for visualising the results of the personnel movement simulations were incorporated into the procedure and toolset developed. Interactive and intuitive interfaces for investigating the results were seen to be essential to place the numerical data contained in the Behavioural Matrix, into the context of the ship design. Initially, the possibility of incorporating modifications to the PARAMARINE-SURFCON software was investigated, but subsequent discussions with GRC indicated that the time required to make

the necessary modifications was beyond the remaining time for the EPSRC project and so this option was not pursued. Instead a combination of existing PARAMARINE-SURFCON functionalities and third party tools was used.

Three types of visualization of the personnel movement simulation output data were considered:-

- **Tabular Data (numerical)** - Certain data produced by the Human Performance Metric (see Appendix B) are best represented in tabular form and the existing spreadsheet functionality in PARAMARINE was used, via the KCL file format. These tables provide detailed information on the performance of the ship population in each of the scenarios simulated.
- **2D Graphical Data** - Line graphs were used to display variations in numerical values, for each of the scenarios simulated, and information on the performance of the ship population and on each of the designated functional groups (e.g. Damage Control, Fire Fighting, and Marine Engineers). The use of relatively simple display techniques, such as line graphs, reveals simulation generated information, facilitates further investigation and assists in making and justifying design choices. In addition, since this type of visualisation uses an existing PARAMARINE functionality, additional tables and customised graphs can be easily added to further explore the simulation results.
- **3D Graphical Data** - In order to fully utilise the simulation results in the early stages of the ship design process, they should be placed in the context of the ship design. This can be accomplished through the use of interactive computer graphics, as in the Design Building Block approach itself.

In the early stages of the EPSRC research project, the UCL DRC investigated the possibility of using existing PARAMARINE-SURFCON functionalities to provide such interactive representations. Although this work showed that interactive visualisations were possible, the resulting file sizes and complexity were seen to be too inflexible for use in the fluid early stages of ship design.

An alternative approach of overlaying 2D images and animations over the 3D model was then investigated. Subsequent discussions with GRC indicated that the time required to make the necessary modifications for this functionality would have gone beyond that allocated to the EPSRC project and so this option was not pursued. However, a visualisation tool based on the Virtual Reality Modelling Language (VRML) was developed. This visualisation tool makes use of third-party viewers, operating within a web browser, which can provide an interactive display with 3D shapes, static texture maps and animated images. This new view of the design can be rotated and zoomed, just as in PARAMARINE, but it can also support interactive animations of the elements of the ship model and can incorporate additional information (e.g. the ID tag and metrics of the watertight door under examination as shown in Figure 3.9.3, page 110).

This visualisation facility was particularly useful in examining the behaviour of the simulated crew in the selected scenarios and relating this to the numerical results from maritimeEXODUS simulations. Despite its effectiveness in informing the designer interactively and intuitively by bringing the personnel movement simulation results into the design context, this mode of presenting simulation results has been separated from the wider design environment (i.e. it allows the visualisation of simulation results in the context of the ship design, but it is

unconnected with the ship design environment). Thus any modification of the ship design cannot be undertaken in this interactive and information rich environment. This can be considered a potentially limiting factor in progressing the design as the designer would have to continually switch between two different environments, potentially inhibiting the wider design exploration. To overcome this, fully developed examples of this type of visualisation, together with the description of their functionality, were submitted to GRC, so they may develop similar visualisation options in the PARAMARINE-SURFCON design environment.

### **5.3 Detailed issues arising from the research**

As highlighted in Chapters 2 and 3, there are several issues identified within this research project, which are seen to be of general applicability with regard to integrating general simulation approaches within Preliminary Ship Design. The development of the interface approach and tools in the project suggested the following issues worth further consideration: information types and explicitness; level of detail; and ease of use with and incorporation of simulation into the preliminary ship design process. Implications of including personnel movement simulation in preliminary ship design have been investigated and compared to current ship design practice as shown in Section 2.6. These implications led to consideration of future developments of wider applicability derived from the work in the EPSRC project and are taken further in Chapter 6.

#### **5.3.1 Granularity: the level of design detail**

While some issues have been addressed in earlier chapters, the significant technical issue of the level of design granularity (i.e. level of detail included in the design)

and of what level of definition is required to obtain meaningful results from personnel movement simulation was considered and is discussed here. As mentioned at the beginning of this chapter, using the method proposed has several advantages, but, in order for the simulation to generate usable information, the ship design model needs to have a certain level of definition (i.e. level of detail as indicated by the number of entities in the design model). This applies not just to the layout description, but also to the organisational and operational aspects.

From a preliminary ship design viewpoint, the effort involved in defining in the model the aspects required to run personnel movement simulations should be reduced to a minimum. In the EPSRC project, the issue of the minimum sufficient granularity level was addressed by making minimal changes to the existing SURFCON model structure, by including additional information while leaving the vast majority of the definition to the interface software required to convert the SURFCON model to the format required by the simulation tool (see Section 3.8).

As a result of the approach the proposed SURFCON model structure consists of the ship's geometrical and numerical description, the definition of connectivity links between Design Building Blocks, the information relevant to manning aspects (i.e. W&SB, crew organisation and personnel characteristics) and the definition of scenarios and procedures. The additional information facilitated a representative model (reflecting the high levels of uncertainty inherent in early stage design) that could then be used to perform personnel movement simulations which will generate useful output. Of key importance was the use of modelling techniques that provided an explicit, unambiguous and consistent definition of the design, which could be resolved by the specific tools to interface

PARAMARINE-SURFCON and maritimeEXODUS data in a reliable and repeatable manner. These tools helped ensure that preliminary ship design models stored a minimal amount of explicit information, which could then be used to rapidly generate the more complex and detailed models suitable for simulation based analysis. These modelling techniques were successful in permitting the interface tools to extract all the information required.

However, the flexibility of the model structure, vital for use in the preliminary design of innovative vessels, may be limited by the level of detail available since this was found to be significantly more than that normally encountered in preliminary ship design models (see Table 3.4.2, page 69). The limited flexibility in the model was considered acceptable, not only in the research context (i.e. that of a development and demonstration project), but also because the issues relevant to the level of detail were found to be amenable to resolution. The two options proposed to tackle this were:-

- a) using semi-automatic routines for inserting the necessary level of detail in a new concept ship model; and
- b) using the personnel movement related analysis tools to provide essentially qualitative results and comparative performance indications.

The latter option meant that the resultant model was not highly sensitive to the reduced detail available in the early stages of ship design.

The above two methods of resolving the granularity issue meant it was necessary to determine what constitutes an acceptable level of detail to run meaningful simulations. How the designer establishes whether the model has a sufficient level of detail to perform a simulation needs further investigation which was not

possible to address directly in the research project. However, the experience gained during the execution of the EPSRC project suggests three possibilities. Firstly, the designer could be left with the responsibility to ensure that the model contains the necessary information, which could be easily tested through a trial and error approach of running a simple set of simulations. A second and perhaps more effective, option, would be the development of a supplementary interface-software as an additional piece of software capable of prompting the designer with a feedback on the level of detail already included in the model. This external module could be added to the automatic or semi-automatic detailing tools outlined in Chapter 3. The third solution would be to force the designer to use a certain model structure which allowed the developed interface tools to automatically resolve the required information. This last option is likely to require significant re-working of the ship design and would certainly add additional complexity plus, potentially, further limit the flexibility of the model. This could be hugely undesirable as it may inhibit the designer ability to creatively explore the early stage solution space.

### 5.3.2 Scenario definition

Another issue that arose as part of the investigation into the level of detail and usability of the proposed approach is that of scenario definition, namely, the description of the scenarios to be simulated. As described in Section 3.6, a scenario is defined by several elements:-

- 1) **A personnel table** (i.e. a comprehensive watch and stations bill - W&SB), which states the location, activities and characteristics of each crew member in each readiness state for the optimal scenarios under consideration;



- 2) **A procedures table** (i.e. a table defining the onboard procedures) which contains all procedural data required for the personnel movement simulation;
- 3) **A setup table** which is used to define some general parameters of the simulations to be carried out (e.g. NBCD, blanket search);
- 4) **A waypoints table** which contains all the significant waypoints used in the simulated evolutions; and
- 5) **An additional table for each scenario** to be simulated defining the sequence of specific actions/activities to be performed by individuals or teams.

The generation and transfer of this data were found to be key elements of the definition of the ship design required to facilitate its integration with the simulation of personnel movement. By including this information in the PARAMARINE-SURFCON model it was possible to directly link the scenario definition to the relevant Design Building Block compartment definitions. The significance of this is that the spatial configuration of the design can readily be changed without the need to re-define the scenario definition. Similarly, a different operating philosophy could be applied to the ship design, by just changing the links in the above five tables required to define the scenario.

Introducing the use of tables as elements to define the simulated scenarios was a major innovation that proved to be very useful in simplifying the definition of arbitrarily complex scenarios without reducing design flexibility. The significance of these developments is that, if the definition of the geometry, connectivity and procedural data are at a defined level, then the scenarios can be automatically exported from the design environment (SURFCON) to the simulation software

(maritimeEXODUS) using the bespoke interface software that was produced.

Despite this level of simplification and automation, including all the relevant information in the tables remains a manual operation and a time consuming task, the process is prone to errors. From the investigations detailed in Sections 2.7 and 3.7, at the time of writing, there does not seem to be any feasible alternative to automating this operation. It is nevertheless possible to generate and use generic scenarios (i.e. pre compiled scenarios of general validity and applicability for a certain type of ship). Generic scenarios for NBCD, blanket search, change of readiness state, etc. could be considered as stand-alone elements defined for a typical naval vessels (e.g. combatants, amphibious vessels, submarines, carriers), but independent of any specific design. They could then be stored in a library of standard scenarios, just like that developed for connectivity items (see Appendix C). These could then be imported and used on a new ship configuration.

Although the option of using predefined scenarios of general validity for a specific type of naval vessel (as described above) has not been fully investigated in this research, the approach to further reduce and simplify the additional effort required by the ship designer to enable personnel movement simulation to be conducted on generic scenarios in early design stages is considered practicable. A possibility would be the importing of a generic scenario setup table from a digital library of scenarios into the model definition, which would be an operation equivalent to importing a SURFCON table. It would then be sufficient to create the internal links between the chosen library items (e.g. locations, waypoints) and the appropriate elements of the ship model (i.e. compartments, complement and equipment items) to be able to run a simulation of the standard procedures

defined in the library of standard scenarios. The linking operation described above can be considered equivalent to the re-pointing of equipment items position and characteristics to parameters used to define the model. Further refinements of these operations are possible and would require, for example, the adaptation of the relevant personnel table (i.e. the table that defines the complement) to the new table inserted in the ship model, thereby integrating the design of the crew with that of the ship.

The scenario library can be considered as a collection of predefined primitive functions and operators and information necessary to generate a scenario definition. Each record in such a library also contains all the basic elements used to describe the agents' logic, behaviour and interactions. These elements can then be combined edited and composed together to create more complex functions as needed by the designer and defined by the user. Each of the scenario library items can be parametrically defined by a number of key factors which could be individually configured thus rendering the whole library adaptable to fulfil the different requirements of any model. Therefore, one of the main benefits of the scenarios library described is that it is directly exportable into any other design project and readily available for use.

There was not sufficient time in the EPSRC project to develop a comprehensive library of standard scenarios, but this could be developed in the future, as part of the continuation of this work, which is under discussion with the UK MOD. Assuming a development project is proceeded with, it could be sensible to include this feature in the toolset that has already been made available by the EPSRC funded research.

## 6 - Conclusions and further research

The discussion in Chapter 5 covers a wide range of issues informed by the research outlined in Chapters 3 and 4. There are several key conclusions that can be made from the discussion on the integration of personnel movement simulation and the Design Building Block approach in preliminary ship design. This chapter presents these conclusions and then outlines proposed development paths. A more general conclusion is that overall aims of the thesis, as stated in Chapter 1, have been met.

### 6.1 Outline of Conclusion

The integration of simulation with the graphically centred Design Building Block approach represents an entirely new way of proceeding with design, demonstrating that a more multi-faceted approach to initial design has become feasible. Thus the ‘softer’ human factors related issues can be given appropriate prominence in the synthesis alongside the classical engineering science aspects.

The integration work outlined can be seen as the start of bringing whole-ship human factors to the fore in preliminary ship design, with the potential to influence major design decisions. The procedural integration of this new simulation domain represents just one significant area where preliminary ship design could be made more responsive to a set of significant aspects of interest not just to owners, but also to operators and end-users. Other significant areas where ship design would benefit from the integration of simulation into the early stages of the design process are, for example, ship motions (i.e. sea-keeping), structural response (i.e. fatigue and strength in intact and damaged conditions) and simulation of combat scenarios.

## 6.2 Main conclusions

The thesis presents the progress achieved in integrating human factors, operability and personnel movement simulation into the preliminary design of ships using the Design Building Block approach, while this chapter presents the main conclusions on the research and outlines future research in the topic.

There are three main areas where this research has provided an original and successful contribution to ship design practice. Those areas are considered to have provided new knowledge and show improved understanding in this regard.

These areas are:-

- a) Production of software that enables the integration of personnel movement simulation into preliminary ship design together with enhancement of the design modelling tools and procedures;
- b) Identification and demonstration of methods to evaluate a ship design with regard to personnel movement performance;
- c) The development of personnel movement scenario descriptions that can be stored in digital libraries, which can then be directly imported and implemented into the ship design software.

The above areas were thoroughly investigated during this research and there are considered to be two high-level conclusions common to all three. Firstly, the solutions identified and developed contribute to the simplification of the designer's main activities, allowing the designer to focus more efficiently on the evolving design. Secondly, the associated methods and tools that have been implemented in the design approach, are directly applicable to and usable in naval ship design, even if this was demonstrated by means of a prototype

version of the system. Both these conclusions are considered for each of the above areas in the following three subsections.

### **6.2.1 Integration of PMS into PSD and design modelling**

The main challenge encountered in this research project was to marry a sophisticated simulation software, requiring a high volume of detailed data and information, with a low-resolution ship design model and to do so to obtain meaningful and useful data, which could inform the design evolution. The study of the feasibility of achieving the integration of personnel movement simulation into preliminary ship design included not only considerations on the technical and procedural aspects of such an integration, but also investigation of the implications of having that capability for the practice of early stage ship design.

The research aimed to bring a wider recognition and a better understanding of personnel related issues to the front end of the ship design process and thereby contribute to a better ship design process through de-risking a given ship design in regard to this aspect of human factors. This was seen to be possible by giving the designer additional and relevant information, presented in a visual and easy to interpret manner, which would increase confidence in the design under consideration. Perhaps more importantly, it also enables a more rapid and effective exploration of the design space at the front-end of the ship design process. That is to say that the designer could explore a number of design alternatives and perform trade-off studies on the design and thus influence costly design decisions.

This thesis presents the first research conducted from a ship design stance extending personnel movement simulation from evacuation (i.e. emergency

egress scenario simulation) into the much larger problem of simulating personnel movement during operations (i.e. non-emergency and non-egress scenarios). The open ended and extensible approach pioneered in this research is seen to offer a number of advantages once the approach is fully integrated into preliminary ship design:-

- The inclusion of the analysis of personnel movement in the design cycle could lead to ship designs with improved whole-ship usability, crew performance, passenger comfort and onboard safety;
- The inclusion of the proposed analysis in the early stages of ship design could lead to a reduction in the effort required downstream to rework the design configuration to achieve improved personnel related performance, with the potential to reduce the time and cost associated with the design process;
- The availability in early stage design of such an analysis approach, with appropriate procedures and toolset could suggest where crew numbers might be reduced and lead to the reconsideration of personnel aspect, such as skills, organisation and hierarchy requirements, through the development of a more efficient design, with the potential to reduce the ship's life costs;
- The inclusion of emergency and evacuation scenario simulation in the early stages of design could lead to safer ship designs and for personnel safety to become an inherent part of the initial design process;
- By introducing personnel movement simulation in the early stage design of ships, this research has demonstrated that there is scope for further integration of wider simulation technologies into this vital

phase of the design process, with further potential for improved designs and reduced costs;

- The research focussed on personnel movement simulation on ships, but the approach and toolset developed have clear applications to other fields of design (such as those of the built environment and large public venues) where demanding physical constraints need to be balanced with large-scale ergonomics, long-term habitation needs and intense personnel evolutions.

The research outlined was undertaken as part of an EPSRC project with the candidate's main contribution focused on interfacing PARAMARINE-SURFCON, and maritimeEXODUS. The aim was to develop a method and the associated tools to enable the interfacing which would be readily useable by ship design teams during the preliminary stages of ship design. In order to produce the prototype toolset which would demonstrate the analysis of personnel simulation movement for both evacuation and operation scenarios, several tools were developed:-

- Modelling techniques within PARAMARINE-SURFCON, representing those ship features needed in personnel movement simulation and analysis;
- Software interface tools to process existing PARAMARINE export formats, resolve the required data in the file formats required by maritimeEXODUS;
- Specifications for additional functionalities and enhancements to maritimeEXODUS core definition enabling the simulation of non-emergency scenarios. (These specifications were then used by the UoG



FSEG team to produce the required modifications and develop the relevant new code and algorithms.);

- The specification of a new analysis method (i.e. the Human Performance Matrix) for evaluating a vessel's performance using the output from the enhanced maritimeEXODUS simulations. This was developed in close collaboration with the UoG FSEG team;
- Software interface tools to process the new types of data produced by maritimeEXODUS simulations (including the development of the definition syntax and export formats of the output files) and translate them into the existing PARAMARINE import formats (i.e. KCL);
- Flexible, interactive and three-dimensional tools for visualisation of simulation results utilising a prototype software developed as part of the work undertaken in this research, the VRML language and a third-party user interface (i.e. VRML viewer). The prototype system developed by the candidate was submitted to GRC Ltd. This gave GRC's development team a specification and an example demonstrating the new functionalities for this capability to be implemented in the future commercial release versions of PARAMARINE-SURFCON.

In making the new simulation based analysis capabilities usable and relevant in the early stages of ship design, this also involved defining the level of model description for use in the analysis. That level needed to be reduced from the level of detailed definition of the design model (or granularity) generally required for such simulation tasks, to that typically available in early stage ship design. This was achieved by making changes to the existing SURFCON model structure

to include additional information, which was then converted to the format required by the simulation tool through an automated process.

Of key importance was the use of modelling techniques that provided an explicit, unambiguous and consistent definition of the design, which could be resolved by the bespoke tools produced to interface between PARAMARINE-SURFCON and maritimeEXODUS in a reliable and repeatable manner. The use of such modelling techniques also allowed the level of automation of the process to be increased while reducing the required level of design model definition. This was necessary since simple computer algorithms are able to calculate all the necessary information from a limited set of initial data in a fast, reliable and consistent manner.

The development of these techniques and the structure of the interface tools produced was greatly assisted by the early, joint consideration by UCL and UoG of the nature, types and format of information that were required to be transferred between the main toolsets. During this process, the development of modelling tools and agreement with UoG on what could constitute good design practice were documented. This helped ensure that preliminary ship design models could store information in an explicit manner, which then could be used to rapidly (i.e. using an automatic computer program) generate design models incorporating all the necessary information required to run personnel movement simulations and analysis.

The modelling techniques described in this thesis were successful in permitting the interface tools to extract all the necessary information. However, some practical limitations were found in that the flexibility of the model structure, vital for use

in the preliminary design of innovative vessels, may be restricted by the additional details incorporated in the model. Most significantly, the level of detail (as indicated by the number of entities) in the design model, was found to be significantly greater than that normally seen as sufficient in preliminary ship design models. These limitations were considered acceptable given the context and aim of this research, but may require further consideration in any future related research.

Several solutions were proposed to ameliorate the constraint on the level of detail. The three main options are seen to be:-

- the use of semi-automatic detailing tools;
- the use of the analysis tools in a comparative, high level and qualitative manner; and
- the modification of the performance measures, within the Human Performance Metric, to ensure that those analyses are not unduly sensitive to the reduced detail generally available in the early stages of ship design.

Ease of use was a key aim for this development phase of the research to ensure the bespoke analysis toolset produced, could be properly incorporated into the preliminary ship design process utilising on PARAMARINE-SURFCON. For this ship design tool, the reduction of the modelling effort required to render the design model suitable for personnel movement simulation ensured that the ship is represented in an explicit manner, which could then be processed by the bespoke software and useable in simulation based analysis. Such reductions were achieved through specialist objects and functionalities, which allow the definition of analysis-specific (i.e. maritimeEXODUS) features. Thus, it is

important to ensure that the process of modelling such additional details and including all the features required for performing personnel movement simulation analysis, will not lead to an excessive burden on the preliminary ship design team, which would preclude its usage.

Ideally, all the designers' effort should be concentrated on producing the ship design, rather than how it should be represented in the ship design software. Furthermore, reduction in the effort required to transfer the ship model definition to the simulation tools and carry out the personnel movement analysis would instead encourage such assessments to be carried out in the vital early, formative stages of ship design.

There are, however, some caveats with this approach to modelling. It is unlikely, for example, that any substitute for the domain-specific technical knowledge required to undertake detailed ship board personnel movement simulation based analysis will be readily found. However, it may be possible to produce tailored made analyses systems that can be used by those not conversant with the full details. Thus for example, for hydrodynamic resistance estimation this has been achieved by ship concept designers. There is also the possibility that domain specific expert simulation practitioners might be brought into or made easily available to the design team. Additionally, ease of use should not necessarily mean "black box". It is also highly desirable that for the concept ship designer understands what information the analysis requires, why it is required and how the software uses it.

### 6.2.2 Evaluation of a design's HF performance

In considering the identification of methods to evaluate a design's human factors performance, this research has shown that it is possible to define a single performance parameter that is representative of the suitability of a vessel's layout for the movement of personnel to achieve its intended use and of the overall design's fitness for purpose in this regard. This parameter was defined as the "Vessel Performance factor" (VP) and its use and associated procedural implications on the design process have been described in Section 3.6.1 and Appendix B. The research showed how this factor can provide the designer with an indication as to the total personnel movement performance of the design when tested against a predefined set of simulated scenarios.

This method for evaluating the human factors aspects of a ship design's operability and personnel movement performance has been shown to be not only a discriminating tool but also a diagnostic one. The technique developed to calculate the VP, not only produces an overall performance score, but also scenario specific performance scores and a score for each functional group into which the complement is organised. If the VP allows a direct comparative analysis between two designs in a qualitative manner, its use as a diagnostic tool, in combination with the additional data and information provided by the Human Performance Matrix (HPMx), from which the VP is calculated, provides identification of the measures that contributed the most to determining the overall HF performance of the design being considered.

The HPMx, was developed with the aim of allowing the systematic comparison of one design of ship layout with another, whether they are variants of the

same design or two completely different designs. The number and type of parameters that populate the HPMx (and that, consequently, contribute to the calculating the VP factor) have been defined as the Human Performance Metrics (HPM).

The parameters included in the HPM can be specific to the type and class of the vessel being investigated thus, for example, an aircraft carrier will have a different HPM configuration to that of a submarine. However, the underlying concept of the HPMx will be common to all types of vessels and some HPM are expected to be similar across different vessel types. The parameters are intended to be extracted from a predefined database where a set of parameters would be pre-selected by the designer, given their appropriateness to the specific type of vessel being considered. However, in the current research it was not possible to develop a comprehensive database, due to the project's limited timescale. Thus, a single set of parameters was determined for the Type 22 Batch III frigate based on the information available from the candidate's naval experience and in consultation with the industrial partner. This set could be seen as the first entry in an eventual performance metrics database for combatant ships (i.e. the Naval Combatant Human Performance Metrics – NCHPM database).

The personnel movement performance data was presented in a logic organisation of the simulations output data. This had been aggregated through the use of weighting coefficients to obtain a single factor and was developed as a demonstration of principle. It represents an answer to the designers' need to understand and manage the insights provided by the personnel movement simulations performed by maritimeEXODUS when exploring different ship

operations and configurations. Its procedural implications and benefits for the ship design process could be further investigated and analysed by a systematic application of the approach as discussed in Section 6.3.

### **6.2.3 Development of a Simulation Scenario Library**

The approach, methodology and tools to render a design model appropriate for personnel movement simulations have been described. This covers the procedural implications of this operation and the main aspects that would enable the proposed integration of PMS into the early stages of ship design to become widely used in ship design practice.

One of the main conclusions on how to achieve this is that the additional operations that designers would have to perform should be easy, intuitive and not prone to errors. In addition, when undertaking simulation projects, simulation specialists employ not just specific software tools but also general-purpose software tools and customised software programs developed to meet the needs of a particular project. Ideally, these different sets of tools should work together in a seamless simulation environment. Modular tools to feed information into the design and simulation environments, such as the ones developed in the project, are one way of meeting this goal. Software modules can be imported from a simulation database and combined as needed. Thus, the simulation scenario can be configured on a case-by-case basis, or even dynamically during the course of a project, with very limited additional work required by the ship designers.

In response to the above, as part of the solutions developed during the project, the candidate devised a digital library of simulation scenarios. This object-oriented Simulation Scenario Library stores scenario descriptions that can be directly

imported and implemented into the design software. This would constitute an operation that was equivalent to importing a series of SURFCON tables. As with the Connectivity Items Library, where access-specific equipment items can be imported, adapted and used, the structure of the scenarios database allows different elements defining a scenario (i.e. scenario modules) to be individually imported and combined to build a complete scenario definition. It also allows the database to the design environment to have transferred to it fully developed and standard scenario definitions (e.g. “State\_1\_Preps” and “IMO\_Day”). This can be seen as a major simplification of the otherwise time consuming task of defining a scenario from scratch, as it offers flexible modelling techniques and undemanding methods for the development of a simulation scenario.

As has been described in more detail in Sub-Section 5.3.2, a complete scenario definition includes the following elements, which are included in the database as modules:-

- a comprehensive Watch and Stations Bill (W&SB);
- a table defining the onboard procedures;
- a setup table of specific simulation parameters;
- a waypoint table with all the significant locations used in the simulation;
- a table for each scenario, defining the sequence of actions to be simulated.

At the time of writing, the Simulation Scenario Library contains data for all the scenarios included in Table 2.6.1 . Each of the modules in the library is designed specifically for the simulation of personnel movement simulation and is founded on the discrete event-driven simulation technique used by maritimeEXODUS [Galea et al., 2003]. Despite this, the Simulation Scenario Library contains data



and information that could render it not just specific to personnel movement simulation, but of general applicability. In fact, the library structure, definition and the code associated with each module are sufficiently general and flexible to allow their use in the definition of other types of simulations. In addition, the standard definition of each item included in the library is of general applicability, but can also be customised by the designer. Each item is parametrically defined by a number of key factors which could be configured by the designer; therefore, the whole library can be adapted to fulfil the specific requirements of different types of simulations.

Although it has not been possible to comprehensively investigate the advantages of using predefined scenarios of general validity for a specific type of naval vessel, the work has shown that the approach is considered practical. Thus the additional effort required by the ship designer to enable personnel movement simulation to be performed on generic scenarios in early design stages has been reduced and simplified. Further refinements of this approach are required, both to develop a comprehensive library of standard scenarios and to extensively test the procedure. This could be performed as part of the continuation of this work, and has been raised with UK MOD, the industrial partner to the EPSRC project.

#### **6.2.4 Final Remarks on Conclusions**

The EPSRC research project aimed at developing and demonstrating the feasibility and validity of the proposed approach, to the extent made possible by the tools and resources made available for the project. From the perspective of the development of new simulation interfaces, for example, it would have been desirable to have import/export capabilities included in ship design

software tools that were as generic as possible, however difficult this might be to program in practice, but the owners of both of the two principle software tools (maritimeEXODUS and PARAMARINE-SURFCON) did not want to have bespoke interfaces and generic interfacing was beyond the project's timescale.

The issues encountered in the research on the integration of personnel movement simulation into early stages ship design have been described and discussed. A means by which the ship designer is able to incorporate such simulation work from the inception of the ship design process has been outlined. It can be concluded that the viability and acceptability of Preliminary Ship Design would be enhanced in the important area of Human Factors and thus the wider aim of achieving a faster and cheaper naval ship acquisition process can be progressed.

### 6.3 Further extension of the research

Possible future research was identified as worth pursuing for future ship design. This is briefly described in the six items below, while the next section outlines the possible extension of the approach to the design of other complex environments.

1. **Innovation.** The approach could be used to develop and to assess the Human Factors aspects for a variety of novel ship configurations and design solutions incorporating novel features. Such investigations would extend the general validity and applicability of the approach and explore some of the limitations of the bespoke software tools produced as part of the research.
2. **Creativity.** The applicability of the method and tools developed could also be considered from the stance of enabling a more creative exploration of the design solution space. The research demonstrated that incorporating the consideration of human factors and operability issues through the use

of simulation techniques, fostered generating and evaluating key creative aspects of complex design. New solutions and ideas could be generated and carried forward by rapidly rearranging tentative design solutions, using the medium of a fully interactive computer graphic interface similar, in principle and basic functionality, to the prototype system presented.

3. **Seakeeping and Stability.** Ship motions and seakeeping characteristics could be taken into consideration when simulating personnel movement onboard, given the ship motion affects the crew's ability to accomplish tasks and move around the ship. For specific types of ships such as small vessels or those with a large number of personnel onboard such as cruise ships, where analysing the effect of the crowding of passengers on one side of the ship could be investigated via personnel movement simulation. Thus the personnel location and movement effects could be investigated for their impact on the vessel's static and dynamic stability, as well as the seakeeping behaviour.
4. **Ship Logistics.** Internal ship arrangements need to ensure easy interaction between personnel, layout and equipment (cargo), especially during embarkation and offload of the payload, whether by landing craft, via vehicle ramp (aft, bow and lateral) and ship-to-ship or even door-to-door transfer. This would require the simulation software capabilities to assess the effects of cargo shifting operations (when loading and unloading in port), onboard vehicles movement and associated personnel movement. Simulation software could be further enhanced to inform the analysis of potential cargo shifting and its effects on seakeeping and stability. Such enhancement would require the simulation software to consider the

combined effects of ship seakeeping characteristics and location and movement of onboard cargo and personnel.

5. **Infrastructure Logistics.** Possible expansion of this research could extend into the preliminary design of port infrastructures needed to support or accommodate ships. It could be possible to consider the interaction between the design of port infrastructure (e.g. terminal facilities) and the design of the ship. Personnel movement simulation could be particularly useful when designing cruise, Ro-Ro and Ro-Pax ships and terminals; simulation of passengers embarkation and disembarkation could improve the internal arrangements of the ship and ashore facilities. This could be integrated in the design of the wider environment surrounding the ship as described in item 4.
6. **Training.** Training of designers and onboard personnel could be tackled using the proposed approach. Additionally insight could be gained from feedback on layout arrangement and investigation of operational procedures obtained by student studies. This could inform future practice thus, for example, exchanging information on how to deal with unusual personnel scenarios, such as piracy.
7. **Mapping the design space.** Early stage design provides the greatest opportunities to explore design alternatives and perform trade-off studies before costly design decisions are made. The approach proposed in this thesis enables the rapid evaluation of the performance associated with personnel movement of competing design options early in the design process. Hence it could be used to facilitate the systematic exploration, investigation and understanding of the characteristics of the design

space in its earliest stages with respect to personnel interaction with the onboard environment. This could improve the operational and manning decision making processes in early design stages by providing the designer with increased confidence in the design and with indications on the direction in which the design is evolving. The knowledge captured in this process of mapping the design space could also result in the development of guidance on effective exploration of design alternatives and, perhaps more importantly, in the production of methodical series resembling those developed for resistance and propulsion [Todd, 1963]. Additionally, in a similar manner to what happened to Taylor's series of systematic empirical hydrodynamic experiments, data obtained by the systematic application of the proposed method to design variations could be integrated in software systems and increase the level of automation in addressing design issues relevant to HF thus further facilitating the process of mapping the design space.

#### **6.4 Extension to the design of other complex environments**

As a consequence of this research, not only could early stage ship design be broaden by addressing HF issues, but also other similarly complex environments could be investigated, leading to a more comprehensive scope addressing HF issues in the initial design synthesis. Such a scope could facilitate a considerable advance beyond the hitherto evolutionary approaches to design practice whereby not only radical configurations and even radical internal layouts tended to be avoided, but also many of the direct concerns of the product's eventual owners and users have not been able to be addressed as part of preliminary design phase.

The new approach to initial general design practice advocated in this research could have wider application than just to the complex ‘top end’ of ship design practice. The changes envisaged to initial design synthesis through the Design Building Block approach constitute what can be seen as virtually an entirely new paradigm for initial design practice, not just for ships, but possibly also for other complex products and environments. The justification for this claim lies in the manner in which the Design Building Block approach to the production of any new complex design can be undertaken, since, as Andrews [2006] pointed out, with this integration of Personnel Movement Simulation into Preliminary Ship Design the design synthesis can now be thought of as being an amalgam of:-

- “i) **algorithmic expressions**: providing simplified numerical descriptions of a class of product plus “rules of thumb” and “best practice” based on experience (numeric synthesis);
- ii) **engineering analysis**: usually of a simplified initial form to identify whether the numeric, and now the graphical, descriptions might lead to an unacceptable end solution for the various discrete analyses considered;
- iii) **graphical representation**: informing both the numeric and analytical computations with a more realistic and comprehensive description (to foster creative synthesis and open up the design space); and finally
- iv) **Simulation Based Design**: addressing the human element of a design, investigating large-scale ergonomics and, consequently, enabling a more comprehensive interrogation of the concept (now made possible by a creative and interactive graphical description of its model).”

This multi-dimensional and multi-faceted way of conducting design synthesis is considered to be both feasible and appropriate for large-scale complex design.

This approach, devised for and developed around complex and multifunctional ships, could be applied to the design of other complex constructions. For offshore structures, for example, the application of the approach developed in this thesis would be relatively straightforward since they differ from ships primarily in their limited mobility and less extensive, if equally complex functions. In the case of the built environment, however, the extent of the changes in initial design practice involved in the adoption of the proposed approach could require considerable change in procedures. Such developments would be consistent with the adoption of the approach of using simulation early in the generation and exploration of the design space, which is readily facilitated by the Design Building Block approach but requiring quite different numeric and engineering analysis to that provided by PARAMARINE for ships.

As proposed by Andrews [2006], the approach of marrying the technical (i.e. numeric synthesis and engineering analysis) with graphical synthesis and the simulation of personnel movement and related operations could be extended to other complex environments. Future environments, for which demanding physical constraints need to be balanced with large-scale ergonomics or HF concerns, such as long-term habitation of outer and inner space, namely space stations and subsea habitats, could be considered in the not too distant future as technology advances and as mankind seeks to exploit more of our own planet and the worlds beyond it.

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## **Appendices**



## **Appendix A - The use of simulation in ship design (software review)**

The purpose of this review is to expose the reader to commercial software packages based around simulation capabilities that are most widely used in ship design by describing some of their main functionalities, capabilities and technical features.

This review was conducted early on in this research to gain an overview and understand the main characteristics and limitations in existing solutions for the integration of design and simulation software tools. The primary objective of this investigation was to collect the necessary information to inform the development phase of the interface software (addressed in Chapter 3) and to be able to implement and/or recommend ways to overcome some of the main issues identified.

Software developers and service providers typically rely on a large number of different tools to cover the diverse spectrum of design analysis and assessments required by designers. Despite the fact that they provide useful features for specific tasks within the design process, those tools are most of the time labour intensive, may require more advanced operator skills and lack the integration level required for easy and seamless integration with other software tools. A common characteristic of the described software programs is, in fact, the lack of integration with the ship design process and relevant software tools, which is normally compensated by extra labour and overlapping efforts from operators in order to select and format information and data to be exploited and exported into other programs. This lack of procedural and software integration is usually compensated by additional requirements for close communication between the various project teams involved in the production of a single design. Naval Architects and Marine Engineers typically use low capability 2D sketching software and/or high-end CAD packages to progress towards a design solution. They sometimes rely on in-house and dedicated proprietary calculation tools to perform the desired analysis. To benefit from these computer systems and optimize the design process, some organizations ought to use very expensive simulation tools operated by highly qualified specialists and requiring labour intensive setup to test and validate each design solution under investigation.

Nowadays, the market offers a very large number of very powerful systems. The most used in ship design are generic 3D modellers like, for example, Rhinoceros, 3Dstudio, Think3Design, Solidthinking, Alias and true solid modellers such as IronCAD, Mechanical Desktop, Microstation, SolidWorks, SolidEdge, PROengineer, UG/solid and Formz. Besides giving a very realistic view of what the designer has in his mind, these software systems allow the creation, already in the preliminary project stage, of a numeric model suitable to become a starting point of the project for further processing. On the other hand, they need a considerable amount of time and this is not an advantage especially considering the flexibility required to enable the creative process to converge to a solution. Moreover, the amount of effort required to use these systems effectively can be disproportionate to the benefits gained since the since the concept and preliminary design phases can be quite considerably altered in their progression and sometimes even terminated if, for example, the owner does not agree to the designer's choices.

In the last decade, the vast majority of design software packages, irrespective of being used in different industries, have gradually moved from an agglomerate of lots of specialist design programs to a more centralised approach and ship design software is no exception to this trend towards centralisation. For example, traditional ship design systems have involved a suite of specialised design programs while modern systems are moving towards the use of a single digital model of the ship, containing all engineering information for the design. In this more centralised approach, the model feeds information into specialist software modules, with a common interface and data format, for analysis of specific features of the design.

Advanced data management tools have been developed to ensure configuration control over the design and to track changes and revisions. These management tools allow control over the data flow throughout the entire design process, from initial and basic design through to detailed product design. Automatic and semi-automatic synthesis tools have also been developed and included within the software suites to speed the development of structural scantlings, production drawings and other aspects of the design governed by rules, regulations and codes. The use of centralised databases and models provides opportunities for effective concurrent engineering processes to take place. As a consequence, the level of models' detail and the confidence in the design have increased at an earlier stage in the design process and the amount of specialist input and re-work efforts required to produce design variants and new solutions can be considerably reduced.

What follows is a review of the software systems that have been investigated as part of this research. These have been organised in two sections as shown in Figure A-1: the first considering commercially available ship design software suites and the second addressing relevant personnel movement simulation software either currently available on the market or under development. For each software programs, there is a short summary of its main characteristics seen as relevant to the objectives of this research and, in particular, to inform the development of the bespoke interface toolset (see Section 3.8).

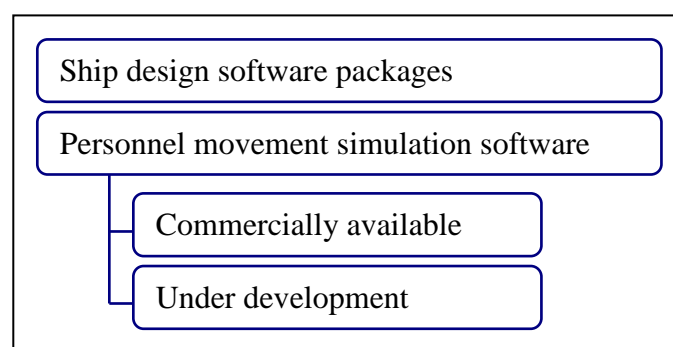


Figure A-1 - The structure of Appendix A.

## A.1 - Ship design software packages

**Tribon** ([www.tribon.com](http://www.tribon.com))

Tribon is a naval architecture program originally developed by Kockum Computer Systems (KCS) for designing commercial and naval vessels. KCS was spun off from Kockum shipyards as an independent company, later renamed Tribon Systems, which was in turn acquired by AVEVA in 2004. Tribon is actually a family of programs that create and refer to a common set of databases containing the design details of the ship. Together, these databases are used to depict a 3D model of the ship, with embedded information for all of the parts of the design, from ship structural elements to pipe segments to equipment.

Tribon is the market-leading system and is currently used by 80% of the world's top 50 shipbuilders<sup>29</sup>. In mid-2002, Tribon Solutions released the latest version of its popular ship design software, Tribon M2. In the first quarter of 2005, seven months after that the AVEVA Group had acquired Tribon Solutions, Tribon version M3 was released. Tribon M3 includes a number of significant new functions such as Clash Detection and Management, analysis tools in basic design and linkage between Tribon M3 and AVEVA's "Review" visualisation solution.

The new Clash Detection and Management function is based on a new proximity and physical space violation (i.e. interference) detection algorithm that analyses large 3D models for clashes within seconds including, if required, any objects that are within a certain capture distance from a specific object. This feature can also be used, for example, for analysis of shock-mounted objects which may vibrate or move in operational to determine service space and access to equipment items.

Information about clashes is stored with the data model and there is a set of management tools for presentation and reporting of clashes. The calculation speed, ease of use and efficient reporting and visualising tools represent important innovations.

Included in the latest release of the software is a new version of the program for transferring the model geometry data between Tribon M3 and AVEVA's Review solution. Review is a visualisation tool used for design virtual inspections and reviews, model "walk-throughs", checking of access routes and creation of photo-realistic images. The two-way link capability also means that Tribon M3 users can import additional information in their models such as, for example, pipe arrangements from PDMS (Plant Design Management System) which is a popular solution for marine outfitting.

The basis of the Tribon system is the Product Information Model (PIM). In essence, the PIM is an integrated product model which is accessed by a number of modular programs each addressing specific issues. All these modules are seamlessly incorporated and interact with the designer through a single user interface. The initial design modules can help in generating hull lines and internal subdivision,

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<sup>29</sup> AVEVA press release (last accessed in 12/2008 - [www.aveva.com/news\\_content.php?id=62](http://www.aveva.com/news_content.php?id=62))

while other modules cover the calculation of hydrostatic data and hydrodynamic performance. At more detailed design stages, outfitting modules for pipes and structure can assist in developing a comprehensive 3D model of the ship systems. Also, production assembly drawings can be generated directly from information included in the PIM and details such as the weld paths can be automatically generated from the geometry of the design.

New to the Tribon M2 software is the Data Management toolset. This module governs configuration control within the PIM, recording revisions changes and controlling the status of the objects as multiple users concurrently work on the same design. An additional service offered by Tribon Solutions is a large internet database of accurate representations of standard parts and equipment items, which registered users can download for incorporation in their projects.

### **FORAN System** ([www.ForanSystem.com](http://www.ForanSystem.com))

FORAN was developed by the Spanish company Sener and the latest version of the software is V50, released in 2002. Its main characteristic is the “Full-ship Product Model”: a central database used to store the all the information relevant to the design model and made accessible to different users simultaneously.

Hullform generation is achieved through the use of NURBS curves and the software is flexible enough to describe monohull or multihull vessels with symmetric or asymmetric hulls. The hullform developed can then be used for naval architectural analysis and further design work. A number of modules are included in the main package and allow estimating the hydrodynamic performance of the vessel using different algorithms, depending on the design characteristics.

Spatial features within the model can be given numerical or topological links, to maintain the design style. A notable feature of the FORAN system is the accommodation design module, which works in both 2D and 3D and can produce arrangement drawings for the interior fittings of the accommodation. FORAN also includes modules to develop the production model, including tools to break the vessel into blocks and to draw up a build strategy for the vessel.

Both FORAN and Tribon use an ORACLE database to manage the product model.

### **ShipConstructor** ([www.shipconstructor.com](http://www.shipconstructor.com))

This software adopts a different approach to FORAN and Tribon, in that it runs inside the popular AutoCAD design and drafting package. The vessel’s model is described by multiple AutoCAD drawings held and organised in a common database. This software is aimed at the development of detail design models and includes tools and modules that assist the design team from the hullform generation, through to the structural definition and up to defining internal outfit and arrangements. In addition, this software can be linked directly with the production line using a dedicated coding language that allows guiding Numerically Controlled cutting machinery directly from the models.

The clever user interface allows a flawless integration of this software with the widely used AutoCAD suite; this reduces the amount of training required to use effectively its characteristics and functionalities, whilst still giving the designer advanced tools for detailed level design. For these reasons, ShipConstructor is mostly used in small and medium design offices and, mainly, for the design of smaller crafts, such as tugs and yachts.

### **AutoShip** ([www.AutoShip.com](http://www.AutoShip.com))

AutoShip Systems Corporation produces a number of ship design software packages, including AutoShip for hullform design, AutoHydro for hydrostatics and stability, and AutoStructure for design of components and management of the production process.

These three tools act as a suite, with common data formats and interoperability, whilst remaining separate environments. A range of parts, hullforms and even entire ship designs are available to download from the companies' centralised database (also available online) for inclusion in users' projects.

As a more recent addition to its software, AutoShip Systems produced a cargo management tool for control of the logistics chain and cargo stowage arrangements. This additional tool is based on very simple simulation routines and is offered as a customised service rather than as a product as it is improved and customised based on specific user requirements. This tool is currently under development and has seen several modifications of its core simulation models and this process can be expected to continue in the foreseeable future.

### **NAPA** ([www.napa.fi](http://www.napa.fi))

NAPA (Naval Architectural PACKage) is developed by Napa Oy (Ltd). The main characteristic of this software is the independence between the design phase and the model assessment phase. In fact, its core module allows a centralised ship model to be defined and/or modified just by a single user while, the same model can be used by multiple end-users simultaneously through a set of standard and/or add-on subsystems used only for its assessment or analysis.

The design is forced by the system to start with the definition of the hullform; the system, however, is very flexible and can accommodate multihulls and asymmetric hulls, as well as offshore platforms. The design model can be analysed by several independent subsystems each of which requires the original model to be enriched with the relevant data and all the details necessary for the correct execution of that specific analysis. The geometry subsystem, for example, allows the design to be worked up to a detailed general arrangement stage, while the "Hydro" subsystems exist to analyse hydrodynamic performance. Additional sophisticated subsystems allow the analysis of stability in intact and damaged conditions and during building and launching; the latest version of this subsystem includes algorithms to analyse some aspects of dynamic stability and parametric rolling. The latest developments in the software include a structural analysis subsystem (NAPA Steel) and the release of "on-board NAPA": a light version of the main suite intended for loading calculations and stability analysis to be performed on-board the vessel while in operation.

**IntelliShip** ([www.intergraph.com](http://www.intergraph.com))

IntelliShip was revealed at the 2002 ICCAS<sup>30</sup> conference. Developed by US company Intergraph Corporation, it is intended to encompass the ship design process from initial design to operation. It can incorporate and evaluate the effects of distributed engineering and lifecycle data management.

The interesting innovation of this system consists of the use of a Smart Product Model (SPM) of the ship in which all parts of the model are hierarchically and logically linked together so that the effects of design changes will propagate through the model, reducing the delay in reworking of the design. The SPM is handled by a Spatial Information Management (SIM) program, which operates using rule-based automated systems and helps estimating the design characteristics from the initial stages and throughout the design process. These Design rules increase the quality of the data describing the model, ensure design integrity and contribute to assuring a high level of automation for design and production. Intergraph also introduced the capability to reference AVEVA Tribon objects and structural designs in IntelliShip. This external capability allows Tribon users to apply advanced Intergraph technology for outfitting while continuing to use Tribon for structural tasks.

Another interesting aspect of the latest release of IntelliShip (version 6.0) is the possibility to automate routine tasks. The user/designer can in fact define and customise rules to drive, for example, the detailing of structural plates and profiles, the placing of stiffener and the determination of weld details, based on the geometry of the connection and on the internal spatial arrangement.

**EDS PARASOLID** ([www.eds.com](http://www.eds.com))

EDS, an HP company, produces a variety of CAD and design management software packages. These include the Parasolid solid modeller and the I-DEAS CAD software. EDS products offer a wide range of life-cycle and process management tools. These are sufficiently generic that they can be adapted to a wide range of engineering applications and integrated in other software programs. Examples are as diverse as the Joint Strike Fighter project, Alstom's Industrial Gas Turbines design and LEGO toys. In these cases, the company has provided design and management software to suit the customer's most varied needs, taking an innovative approach to virtualization. EDS, in fact, focused not only on hardware or software capabilities, but also on proper information management and logic orchestration of the model's hierarchy. Combining virtualization technologies with visualisation techniques and applying appropriate interface solutions to meet designers' needs has proven to be a successful strategy.

PARAMARINE uses the Parasolid kernel developed by EDS. The use of this standard kernel enables its object-oriented characteristics, allows the flexibility in the defined geometry and in the description of specific features of the ship design.

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<sup>30</sup> The International Conference on Computer Applications in Shipbuilding (ICCAS)

**CATIA** ([www.3ds.com /products/catia](http://www.3ds.com/products/catia))

IBM has developed several software tools dedicated to both engineering design and Product Lifecycle Management (PLM). CATIA is one of these tools and is a specialised software that allows the development of a “digital mock-up” of the product being designed. Designed to addresses original equipment manufacturers (OEMs) and their supply chains, CATIA addresses the complete product development cycle from product concept specification through product-in-service and facilitates true collaborative engineering across disciplines, including style and shape design, mechanical design, equipment and systems engineering, digital mock-ups, machining, analysis, and simulation. CATIA uses a centralised database containing all the data and information relevant to the definition of such a model, thus permitting concurrent engineering practices to take place and the enforcement of design rules and specifications to be assessed. Using the same centralised approach, in fact, the ENOVIA solutions is a suite of software packages intended to support the design and lifecycle management of a product. The innovative aspect of this suite is the extensive use of web-based portals and PPR hubs (Product, Process and Resource hubs) to enable and facilitate the exchange of information between the different members of a project team and/or communication between different design teams.

Specific solutions developed for the shipbuilding industry include AEC hull design. This is a structural design software based on standard parametrically controlled parts and algorithms to automatically generate production information for the design. AEC and other ship design packages can also be used to generate a Virtual Reality (VR) environment of the ship, which enables the design team to visualise, gain a better understanding and assess the layout of the model under development. The VR visualiser can also be used to address human factors aspects in the design and operation of the vessel.

Facilitates true collaborative engineering across the multidisciplinary extended enterprise, including style and form design, mechanical design, equipment and systems engineering, digital mock-up, machining, analysis, and simulation.

## A.2 - Commercially available simulation software packages

The computational models reviewed in this section have been analysed because they are widely acknowledged to be the ones capable of efficiently simulating personnel movement simulation. A common trait of these software packages is that, due to the scarcity of precise behavioural data, they tend to rely heavily on assumptions and it is not possible to gauge with confidence their predictive accuracy. Validation in simulation defines the process of ensuring that a model represents reality at a given confidence level and that the model is a reasonable representation of the actual system. In the past decade there has been increasing interests in studying simulated human factors aspects in emergencies and non-emergency scenarios [Shields and Proulx 2000; Proulx et al. 2002], however, the fundamental understanding of the sociological and psychological components of personnel movement behaviours is left wanting [Galea, 2003b].

What follows, is a summary of the major simulation systems currently available in the market and a brief description of their main characteristics, peculiarities and capabilities. Any simulation software, in general, is only as good as the underlying algorithms that are implemented in its code are, but the scope of this review was limited mainly to the type of results produced and to the characteristics of the user interfaces. The review specific focus is on the most innovative features and on the possible contribution to inform the design process this software programs offer.

### **AutoMod** ([www.multicim.com](http://www.multicim.com))

AutoMod is a 3D modelling and simulation tool designed for the analysis of manufacturing facilities, automated material handling systems, logistics and distribution industrial farms. AutoMod can import geometries from the most commonly used CAD systems and includes an object based CAD editor that supports 2D and 3D modelling manipulation of such geometries. After the objects and graphics have been created, additional logic can be added to detail the behaviour of the defined entities. This can be achieved through a simple integrated spreadsheet interface and either by using the AutoMod generation language or by coding C and C++ routines. Although this tool allows simulating the interaction between moving equipment and personnel, it is not particularly suitable for simulating human behaviour. This limitation is ascribable to the deterministic approach followed by the underlying algorithms: every event has to be pre-programmed and defined in detail before any simulation can be performed.

AutoMod can automatically generates output reports; these can be displayed in real time using tables or graphics while the model is running or, as a summary, after the simulation has completed running. Standard and custom statistics and sequence information are gathered and can be examined within the program or exported as text files for easy edition and importation into other applications. This external compatibility is a very interesting capability that opens up opportunities for integration with other design and analysis tools.



**Crowd Dynamics** ([www.crowddynamics.com](http://www.crowddynamics.com))

An interesting approach to simulate the behaviour of large crowds was developed by Dr. Still, mathematician and computer scientist [Still, 2000]. His approach has been implemented in a commercially available software tool: Urban Analytics Framework (UAF). The approach and underlying math are based on complex multi-dimensional differential equations and fractal algorithms replicating the “least effort behaviour” of single agents in large groups of people, both in normal and emergency scenarios. The core simulation model (namely Legion) consists of independent problem-solving entities which obey a set of predefined rules (and not instructions) able to replicate real world observed agent behaviour. These entities can move around a two dimensional computer-generated landscape and read and react to changes in that environment; these reactions also include responses to physical changes in the layout, events such as fire and explosions and the behaviour of other entities.

Combining a traffic micro-simulation model with a fully featured free space agent model allows the UAF to accurately reproduce a wide range of scenarios. The UAF can also be used to model moving objects (such as vehicles) and the agent’s interaction with such elements.

Given the scope set for its development (i.e. urban space design, analysis of the movement of goods and people in modern urban cities), UAF requires a very detailed description of the environment and is quite accurate in its predictions when a large number of agents are considered in very close proximity and in a large environment. There are also limited possibilities of defining agents able to follow procedures and/or to follow instructions since agents’ behaviour customisation is restricted and not programmable.

**SURVIVE** ([www.qinetiq.com/survive](http://www.qinetiq.com/survive))

Originally developed by QinetiQ and its predecessors for assessment of ships and submarines, SURVIVE is a sophisticated marine survivability assessment suite. This prototype software solution is the result of a study aimed at demonstrating the feasibility of integrating vulnerability models to assess the impact on ship survivability against above and below water damage.

In the developers’ view, the overall survivability depends on susceptibility (the likelihood of a platform being hit), vulnerability (the effect of damage caused to a platform’s operational capability) and recoverability (the capability of a platform to restore functionality post hit). One of the primary factors in the recoverability phase is the crew performance. In this respect, SURVIVE is capable of accurately modelling crew and equipment movement around the vessel. This is achieved by simulating and tracking crew members individually using a nodal network model to calculate available routes through the ship. It should be noted that the behaviour of each automata is defined by few simple rules, common to all crew members, while the network of available routes is dependent on the scenario considered. For example, a smoke-logged passageway will only be available to crew using breathing apparatus.

The key algorithms used in the simulation were derived from trials and numerical analysis and the results have been validated against those trials data. The parameters defining each crew member in the model are function of its location, role in the organisation and physical status (e.g. reduced mobility due to injury); all these characteristics are parameterised and stored in a skills matrix. The simulation of crew behaviour also takes into consideration evacuation scenarios including an interesting feature for escape scenarios in port where the ship's environment is connected with the "rest of the world" not only from a geometrical point of view, but also from a crew awareness standpoint (e.g. the availability of additional resources ashore). For vessels at sea the evacuation is simulated by the crew proceeding to the designated mustering zones, while the evacuation of moored vessels can be extended off the vessel and through the surrounding areas of the port.

SURVIVE has a number of flexible and interactive tools to present the user with the simulation results and data are summarised to give clear indications to swiftly inform the design process. Effects of design decisions can be readily seen and quickly evaluated while a number of interactive viewing modes allow the user to get the required details and information from the output data.

SURVIVE can simulate a wide range of scenarios in a very realistic manner, but requires a very detailed model of the ship and an accurate representation of the onboard systems. Building such a complex model is a demanding task and requires a considerable amount of time and experienced users, particularly because very little information is importable from CAD systems or other modelling tools. Moreover, the simulation is computationally intensive and unsuitable for use on personal computers. With the intention of overcoming these issues and of facilitating design assessment in the earliest design stages, QinetiQ has developed "SURVIVE Lite" a concept vulnerability analysis tool for rapid prototyping and initial design optimisation.

A PARAMARINE output to SURVIVE has been developed on behalf of the MOD and, given QinetiQ's recent acquisition of GRC Ltd. it is envisaged a possible higher level of integration between the two software tools.

#### **AENEAS** ([www.gl-group.com](http://www.gl-group.com))

The know-how behind Germanischer Lloyd's AENEAS comes from TraffGo ([www.traffgo-ht.com](http://www.traffgo-ht.com)), a company founded out of the Physics of Transport and Traffic Department of Duisburg University led by Prof. Michael Schreckenber. This innovative computer tool is a leading edge passenger evacuation model specifically targeted to fulfil and comply with the IMO requirements for RoPax vessels (MO MSC/Circ. 1238). The major innovation resides in the simplified and targeted analysis, in the very high speed of calculation and in its reliability in assessing whether a design conforms to IMO evacuation requirements. The "as complex as necessary, as simple as possible" approach this tool is based on delivers very realistic results when compared with real scale test measurements. Along with the development of the model, considerable effort has been devoted to optimising the calculation procedures and the underlying algorithms. Because the ultra-short computation times permit performing several thousand simulations a day, a reliable statistical basis for the evaluation can be obtained.

In fact, because of the statistical distribution of the parameters defining the agents, the result of the simulation can vary a lot. In addition, the statistical decisions making algorithm of the simulated persons spreads the outcome of the simulations even more. This is why every simulation run provides a different evacuation time, just like it would happen in reality. Since a complete evacuation analysis requires performing about 500 simulation runs to be statistically satisfying, simulation and computational speeds are of paramount importance.

A DXF interface allows AENEAS to import the geometry of multiple decks ensuring compliance with most CAD systems and a smooth integration during any phase in the design process. It has to be noted that particular attention was given to its usage during early design stages and specifically in the pre-contractual phase. Information on passenger locations, egress routes and muster or disembarkation stations can be graphically included in the CAD drawing. Alternatively (or in combination), an open XML format can be used to specify evacuation routes and directions, exits and passenger and crew locations in each scenario. Flexible and programmable pre-processing procedures can be tailored to meet any drawing conventions and allow for semi-automatic input into AENEAS.

In the simulation, each agent has his own set of rules defining abilities, specific skills and personal preferences to advance towards his goal (the agent is given the simple objective of reaching a particular muster or assembly station). No group behaviour has been implemented and it is not possible to define additional tasks; consequently, the overall evacuation scenario results from the self-organized movements of each agent toward their destination.

This tool is designed to analyse evacuation in marine vehicles ranging from HSC and small vessels (with less than a dozen persons) to large cruise ships (with several thousand passengers and crew). The applicable rules and statutory regulations are considered during the simulation.

### **SimWalk** ([www.simwalk.com](http://www.simwalk.com))

SimWalk is an agent-based micro-simulation software focused on traffic engineering in architecture and urban planning applications, evacuation and traffic management. Every single pedestrian is modelled individually with a specific goal (reach a destination) and behaviour. The behaviour of each agent is randomly selected from a database of experimental data, ad hoc formulas and general information on pedestrian behaviours. The pedestrian algorithms determine the agents' movements; pedestrians move directed by the shortest path to destination, avoiding congested areas and other pedestrians. Due to the statistical nature of the core model, SimWalk is particularly reliable when simulating large crowds. The software's core module allows flexible and realistic simulation of normal as well as panic behaviours of pedestrians in relatively simple environments. The environment is 2D and its geometry can be directly importable from CAD files. The latest release of the software has a multi-level capability (i.e. allows to model, for example, multi-storey buildings) and supports different level interconnection objects like stairs, escalators and elevators.

The main feature of SimWalk of interest to this research is the large number of counters recorded during the simulation (parameters useful to numerically analyse the simulations' output) and the way they are stored and presented to the user. These data include, for example, flow rate analysis of pedestrians, density (congestion and space utilisation), walking speeds, flow rates across pre-determined areas and times to reach certain waypoints and the final destination. These numerical results can be directly exported into Excel format for analysis or used in a separate visualisation tool.

### **SeSAM** ([www.simsesam.de](http://www.simsesam.de))

SeSAM (Shell for Simulated Agent Systems) provides a generic environment for modelling and experimenting with agent-based simulation. This free tool allows the easy construction of complex models which can also include dynamic interdependencies. SeSAM is completely based on visual agent modelling; many concepts of traditional programming have been included and are provided in an intuitive environment for drag-and-drop modelling. The user can create agents by modelling their behaviour with activity flow diagrams while scenarios can be created by placing agents in a two dimensional map and assigning them tasks and objectives. The latest release also includes a feature that supports modelling simulations with an event based schedule.

The software has a library of predefined primitive functions and operators, the basic elements used to describe the agents' logic, behaviour and interactions. Primitive functions can consider sensing or acting and they can be composed together to create more complex user defined functions. Operators range from simple Boolean operations to genetic algorithms. As such simulations can get computationally intensive; there is an option to distribute simulation runs across a network of computers or within the local network. Simulation results are saved to the hard drive and can be collected after the remote simulations are finished. SeSAM also offers a wide variety of integrated functions for visualising model results and tools for analyzing simulation results. There are freely configurable instruments for gathering data and scripting options for constructing simulations.

Given its general applicability, SeSAM was designed as a stand alone simulation environment; consequently, some functionalities are missing. For example, importing information such as geometry from CAD programs or data from external databases is impossible. Moreover, the geometry producible within the software is two dimensional and has to be programmed rather designed.

### **QUEST** ([www.delmia.com](http://www.delmia.com))

Originally developed by Delmia (formerly Deneb Robotics Inc), Dassault Systèmes' QUEST (QUeueing Event Simulation Tool) is a 3D, physically-based simulation product used to analyse industrial and service-related environments [Hugan, 1994]. QUEST is a general purpose discrete event simulation tool designed to assess logistic systems based on both object oriented as well as simulation language approaches to modelling. As part of the design of the next generation Naval

Amphibious Transport Dock Ship (LPD17) this simulation tool was used to evaluate the arrangement and flow of cargo on the ship and to integrate material flow concepts with the overall design requirements [Hugan, 2000].

QUEST models are constructed through the combination of a few basic entities linked by physical and logical relationships. Each of these entities has characteristics and default logic options that facilitate rapid model construction. Built-in logic options are written in a high-level procedural language and all of the routing and processing options are available for user modification. The simulation engine is deterministic in nature, adopts an approach based on queuing theories, uses shortest distance algorithms and assigns knowledge of the geometry of the modelled environment to its agents. Given the software scope and consequent architecture, possibilities for personnel simulation are limited to a predetermined set of tasks while the ergonomic assessment of the design is impractical as it would require a complex coding effort. Interestingly, however, the simulation output can include information on workload and fatigue.

QUEST's architecture supports sharing data with other software packages; for example it integrates a wide range of data translators for importing and combining geometry from many different CAD packages into the same flexible and tightly integrated environment. Once the model is loaded, the model goes through a series of scenarios and missions to evaluate the wide variety of tasks that the ship will be asked to meet. As successive runs are executed during a given session, the system keeps track of all the simulation data for comparative analysis. Batch reports are also automatically generated for analysing trends. Reports can be displayed within the software and/or exported to a single ASCII file for subsequent integration with other applications.

One of the most interesting characteristics of its architecture is the distributed nature of the data model. Model information is not saved in a single file; instead, the model file contains a series of pointers that import the most current version of graphical or logical data each time the model is used. This automatically keeps the model current and greatly reduces the amount of redundant data in each project file.

### **PEDROUTE** ([www.halcrow.com](http://www.halcrow.com))

PEDROUTE is a pedestrian movement simulation model originally developed at London Underground Limited (the intellectual property rights belong now to Halcrow Group Limited). Pedroute has been designed and extensively used to model crowd parameters in underground networks and to simulate passenger movements, congestion and capacity within their stations.

The suite comprises four distinct components: Network Builder, Simulation Module, Graphics Module and Analysis Modules. The physical layout is generated from imported CAD data and populated with various 'blocks' to represent the functional use of the spaces and their connections into a network of possible routes. Typically, a model would incorporate multiple levels with inter-level connectivity items (i.e. stairs, escalators and lifts) and their population. The occupancy of the network is represented by a population of 64 different 'person-types' to

accommodate variations in factors affecting decision making processes and movement characteristics (i.e. walking speed, baggage handling, personal schedule, etc.).

Interestingly, the model uses several different techniques to assign one of the available predefined behaviours to the simulated passengers. Consequently, these algorithms can be used to simulate different behavioural and physical layout scenarios. The techniques range from fixed route to dynamic assignment using equilibrium or stochastic assignment algorithms [Buckman and Leather, 1994].

The Simulation Model can produce a detailed simulation of the movement of passengers around the network using dynamic assignment process [Halcrow, 2003]. As output results it provides statistics of the individual passengers journeys, delays and congestion experienced in tabular format. This information can then be visualised and studied using the Graphic and Analysis modules.

The main problem associated with this system is that it is based on assumptions which are questionable with respect to field observations. Assuming a predefined speed to density relationship, for example, can be inappropriate to the understanding of crowd dynamics. On the same grounds, PEDROUTE suffers inaccuracies when dealing with cross flows, multidirectional concourse areas and scenarios with low occupancy density. In those cases the closest approximations are made, but accuracy and credibility of the results drop dramatically. This is not to say that the PEDROUTE Modelling systems should be discarded. Indeed, within the described limits it provides ample safety margins which fully comply with the building design guidelines and regulations.

#### **EVI** ([www.safety-at-sea.co.uk/evi](http://www.safety-at-sea.co.uk/evi))

EVI (EVacuability Index) is one of the main passenger evacuation software developed specifically for the marine environment and capable of real time evacuation simulation in large cruise ships and RoPax vessels, whilst accounting realistically for both human and ship behaviour.

The computer program, developed by SSRC (Ship Stability Research Centre, [www.ssrc.na-me.ac.uk](http://www.ssrc.na-me.ac.uk)) at the Universities of Glasgow and Strathclyde and now managed by Safety at Sea Ltd., is fully compliant with the IMO's interim guidelines for ship evacuation (IMO, MSC Circ.1033/2003). The present release (EVI 3.2) addresses ship evacuation issues going beyond the IMO guidelines by introducing a number of innovative features (described below) particularly useful to achieve accurate and realistic results when simulating ship abandonment operations.

EVI is one of the few tools to use continuous space modelling (the simulated environment is not discretised in nodes but used as a continuum). A modelling application allows the user to import any ship layout directly from DXF drawings and to add all the geometric elements needed to conduct the simulation (e.g. doors, stairs, lifts, etc.). These predefined elements are selected from a database, but some of their characteristics (e.g. door width, lift speed, etc.) can be modified through customisable parametric controls.

The incorporated multi-agent evacuation Simulation Modelling Tool allows defining passenger/crew demographics and distribution. Closely connected with this module, a scenario builder allows to include topological information (e.g. primary route identification), assign semantic properties (e.g. functionality of a lift or of a Life Saving Apparatus) and define schemas for evacuation (e.g. a global path plan can reprogram passenger agents to follow assigned routes different from the shortest route). In addition to defining evacuation scenarios and procedures (e.g. mustering stations assembly, embarkation, launching of life boats, etc.) it is also possible to consider different evacuation strategies (abandon ship, transfer to refuge centres or a combination of the two) and the consequences of a range of possible incidents (e.g. fire, collision, progressive flooding, cargo shift and foundering).

Interesting is the way the adversity of the sea-ship environment is modelled and taken into account during the simulation. Dynamic ship movements (imported from an external seakeeping program) exacerbate agent's disorientation and reduce their mobility. In a similar manner, imported Fire FED<sup>31</sup> and Flooding data influence the simulated scenario; for example, flooded spaces become inaccessible and damaged equipment items unusable.

Deriving from the ships' geometric complexity, Modelling human behaviour in terms of way-finding and path-selection is a difficult problem to address and resolve. In addition, most aspects of human behaviour are exacerbated by the dynamic movement of the ship and by psychological and physiological aspects. Human behaviour parameters are non-deterministic quantities and have been modelled with some built-in uncertainty: every parameter is modelled as a random variable with a predefined distribution while the simulation core model is based on the Monte-Carlo method. Taking into account so many contributing factors influencing the simulation presents issues in terms of processing capacity and information handling. This also requires a considerable and time-consuming effort to set up the simulation correctly and results in extensive calculation time to perform simulations. To obviate the latter issue, EVI can use the EviNet, a protocol to distribute the computational load across a network of connected computers.

The simulation results can be visualised in a 3D virtual reality environment allowing the progress of the evacuation to be fully appreciated. Any congestion or locations of bottlenecks can be easily identified and examined in an interactive manner. Furthermore, the tool features full telemetry and playback options so that the user can review, replay and analyse the results at any time during the simulation or after its completion. The user can define and export every result and metric of interest but the program allows selecting from a predefined list that includes relevant information (e.g. queue lengths at each door, occupancy of each region, deck clearance times, cumulative crossings history of specific regions, congestion time history, etc.).

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<sup>31</sup> FED (Fractional Effective Dose) data take into account the influences of fire, smoke or gaseous asphyxiants on people. The underlying assumption is that exposure to toxic substances and hazardous environments but also the effects of heat and cold sum up until incapacity or even death occur (regulation 17, chapter II-2, SOLAS 2000).

Two additional functionalities, not present in any of the investigated tools, are of particular interest: the default distinction made between crew members and passengers and the agents' capability to communicate and interact. As previously mentioned, a variety of tasks can be assigned to agents individually or to groups but crew agents have a greater range of functional objectives enabling evacuation procedures to be more realistically modelled. In addition, through a "messaging" mechanism crew agents can directly control or affect the behaviour of passenger agents and ultimately the overall simulation process. Messages can also be sent between passengers (for example, informing each other of the presence of blocked doors) and the system provides the basis for the simulation of a public address system.

### **Legion Studio and Legion 3D** ([www.legion.com](http://www.legion.com))

Legion Studio is a widely adopted, powerful and accurate pedestrian simulation software. It comprises three applications: the Model Builder, the Simulator and the Analyser. In combination, these three applications simulate pedestrian movement within a defined space (e.g. railway stations, sports stadiums, airports, tall buildings, transport hub, town centres etc.). The core model of the software simulates the pedestrians' movement footstep-by-footstep – in a quantitatively verifiable manner – calculating how individuals interact with each other and with the physical obstacles they encounter in their environment.

Legion Studio allows performing virtual experiments on the design or operation of a space and assessing the impact of different physical designs or levels of pedestrian demand. It accommodates the possibility of studying the impact of chance events (e.g. closure of an exit, unavailability of a certain route, etc.) and test different evacuation scenarios for speed and safety. Of particular relevancy for this research is the operational simulation. This module uses a fully integrated suite of traffic and transportation analysis tools (Aimsun NG - TSS product, <http://www.aimsun.com>). This provides an integrated platform for both static and dynamic modelling and can be used for transport planning, microscopic traffic simulation, and demand and traffic data analysis. The combination with the compelling, visual nature of Legion Studio's simulations, maps, graphs and videos make this integrated software a highly effective and persuasive decision-making tool.

Legion 3D handles complex, multi-level environments and operational scenarios and produces outputs based on the actual data from the simulations. Despite its flexibility, the software is quite complex to use and is not conceived to support the design process, but to assess the performance of a given enclosure against emergency scenarios (e.g. fire, smoke, terrorist attacks) or in controlled traffic simulations (e.g. road congestions, city planning).



### A.3 - Personnel movement simulation tools under development

There are several tools currently under development in universities around the world representing the forefront in this research field. Each software package introduces innovative characteristics that influenced the work conducted as part of this research.

#### **UrbanSim** ([www.urbansim.org](http://www.urbansim.org))

UrbanSim is the centrepiece of the research activities of the University of Washington Center for Urban Simulation and Policy Analysis. It is within this planning context that the UrbanSim model has been developed. The model, in fact, implements a perspective on urban development simulation that represents a dynamic process resulting from the interaction of many actors making decisions within the urban environment. This software is based on a core model that is behavioural in its approach and it is able to capture complex interactions not only in the simulated population, but also in the markets for land, development, and transportation. It is a valuable tool for improving the level of understanding of how a metropolitan region is developing and how various combinations of land use, transportation policies and investments are likely to shape these trends [Friedman et al., 2008].

The UrbanSim software, including full source code, is available for download via its website and is licensed under the GNU General Public License, which means it is free, open source and any derived works are also covered under the license. This is the first interesting aspect of this software since, in the past, modelling systems have largely been “black boxes”, understandable only by experts in the field and non-transparent to the user [Waddel and Ulfarsson, 2004].

There are two main aspects of UrbanSim that are of interest to this research: the integration of a cost analysis model, used as an additional decision making tool made available to the designer, and the module for the analysis of output uncertainty, which provides an indication of the confidence in the validity of the data in output. Describing these modules goes beyond the scope of this review, but valuable information has been gained by understanding how these indicators provide the principal means for presenting UrbanSim simulation results to the users so that the results can be assessed, compared and used to inform the design process.

#### **Mobilis and DISTRIMOBIS** ([www.physicsofthecitylab.unibo.it](http://www.physicsofthecitylab.unibo.it))

The projects and the researches leaded by the “Physics of the City Laboratory” of the Alma Mater Studiorum - University of Bologna, Italy [Bazzani et al., 2007]. In this software, any simple movement is the result of complex interactions between the external environment and the individual cognitive dynamics of the automata. The proposed models have mainly considered a deterministic point of view to describe the choice of the pedestrians’ trajectories and to study the critical congested states. It has been pointed out the importance of the individual free will in determining both the microscopic pedestrian behaviour and the emergent properties of the crowd dynamics.

In this software the developers have implemented a hierarchical model (namely Mobilis) for pedestrian mobility whose emergent dynamical properties are determined by the bottom-up and top-down actions among the microscopic-level (free-will level), the mesoscopic level (deterministic level) and macroscopic level (cognitive level). The programmed automata have an internal cognitive dynamics and can simulate both physical and information based interactions using a vision mechanism. Interestingly they are also able to compute a cognitive map representing the geometrical space they have knowledge or experience of. The Mobilis model and its principles have been implemented in the DISTRIMOBs simulator: a program designed to simulate a whole city on a distributed architecture.

In synthesis the Mobilis implementation in DISTRIMOBs has the following main characteristics:-

- A pedestrian mobility model based on physical models such as gas-kinetic ones;
- A distributed simulator with an agent-based model.
- A simulator able to predict the pedestrian mobility behaviour from the small scale (internals of building, exhibitions, etc.) to the large scale (whole cities including public transport systems).
- A computerised model able to reproduce pedestrian behaviour using evolutionary techniques.

The main innovation in this software is the motivational model implemented in the agents' behaviour algorithms (i.e. what drives the agents' behaviour: motivation guides artificial intelligence algorithms in choosing which goals to reach and in which order). The motivational model developed is an unsystematic mobility one. Unsystematic mobility is a kind of mobility, different from the traditional origin-destination one. Origin-destination models simulate entities (single or aggregated virtual persons) simply going from a source to a destination; so every entity has a single goal and when this goal is reached the entity leaves the simulation.

Simulated persons of asystematic mobility models move without a single and predefined goal, but with a set of possible goals from which to choose depending on the situation. The motivational model has a source of motivations: an algorithm running continuously inside the agent taking into account simulated person attitude, internal status and free will, but also the state of the environment as perceived from the agent itself. Free will is implemented by randomization and is upstream with respect to motivations in the artificial intelligence layers, where the lowest layer chooses the next step.

### **EVAS Pedestrian Modelling Software** ([www.vr.ucl.ac.uk/research/evas](http://www.vr.ucl.ac.uk/research/evas))

EVAS (Exosomatic Visual Architecture System) is a software program developed at University College London in the Bartlett School of Graduate Studies by the VR Centre for the Built Environment team [Turner and Penn, 2002].

EVAS is based around the principles of Gibson's ecological theory of perception (Gibson, 1979) which are more commonly used in computer vision and robotics. In fact, few have applied Gibson's approach to agent-based models of human movement, because the ecological theory requires that individuals have a vision-based mental model of the world and, for large numbers of agents, this becomes

extremely expensive computationally. Thus, within current pedestrian models, path evaluation is largely based on calibration from observed data or on sophisticated (but deterministic) route-choice mechanisms and there is little open-ended behavioural modelling of human-movement patterns.

One solution, which allows individuals rapid concurrent access to the visual information within an environment, is an 'exosomatic visual architecture', where the connections between mutually visible locations within a configuration are pre-stored in a lookup table (i.e. in a database). EVAS demonstrates that, with the aid of an exosomatic visual architecture, it is possible to develop behavioural models in which movement rules originating from Gibson's principle of affordance are utilised. Large numbers of agents programmed with these simple rules and utilising the exosomatic architecture applied to a built-environment generate aggregate movement levels very similar to those found in an actual building context.

The software encodes natural movement as an agent-based system and offers an interesting approach to pedestrian movement modelling achieved through spatially-aware agents (i.e. spatial agents). The system gives agents simple visual perception of their environment and the agent's decision making algorithms are influenced by the input received from such a visual system. Spatial agents use vision to assess the configuration of the simulated environment and move towards open spaces by a stochastic process: choosing a destination at random from the available ones (i.e. visible open spaces) and walking towards it. In this way, they are configurational explorers. The main rules embedded in each agent consist in an extremely simple logic loop: look around and choose a destination, walk few steps towards it, look around, if available choose a new destination, walk toward destination, and so on. If their field of view is set to 170° (approximating human vision) the agents start to move, on aggregate, in a human like manner.

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## Appendix B - The Human Performance Matrix (HPMx)

Crucial to the success of this project has been the definition of suitable Human Performance Matrix (HPMx). This database of information provides the human dynamics criteria by which the HF suitability of the vessel layout can be evaluated and is inherently specific to the type and class of vessel being investigated. For example, naval vessels and passenger ships will have very different HPMs; equally, an aircraft carrier will have a different HPM to that of a submarine, as will a cruise ship compared to a high speed craft. However, the underlying concept of the HPM is common to all types of vessels and some of the various components that make up the HPM may be similar across different types of vessels.

A list of measures has been produced by the candidate (see Table 3.6.1, page 82) establishing which behavioural components might be of value to the ship designer; i.e. those aspects of the crew function which can be represented numerically. A sub-set of these components forms part of the measures included in the HPM in order to represent those conditions that are of general interest. The actual measures included can then be modified as the understanding of their relative importance develops, although the list is sufficiently general to encapsulate a variety of different maritime scenarios. As a result, some of the measures may have little value in some of the scenarios being examined and this will be addressed in the HPM (represented as a numerical matrix) through the use of weighting coefficients modifying the contribution of each measure to the overall personnel movement 'score'. These general measures include, for example, the time spent during the simulation at critical levels of congestion, the predicted number of resulting fatalities (in the extreme case of evacuation), the time spent in preparation, the time spent performing actions, the time spent in transition, the total simulation time and the number of operations performed.

In this research the primary focus is on naval vessels and in particular escort type surface combatants and hence the HFM will reflect this i.e. as Naval Combatant Human Performance Metrics (NCHPM). If successful, a number of HPM could be developed for different types of vessels. For demonstration purposes in addition to the two IMO evacuation scenarios, three additional scenarios have been investigated. These are the performance of a blanket search (as part of a damage control evolution), a change of readiness state (e.g. defence to action stations) and a family day visit by the public (see Table 2.6.1, page 45). Furthermore, some of these will also be examined when the ship is at a 20° angle of heel.

The definition of the scenarios involves: number of crew, crew starting locations, crew response times, crew duties, crew target locations and allowable routes. All scenario definitions have been undertaken in consultation with the MoD partner, namely, the Sea Technology Group (STG). The developed approach and tools also allow defining for each scenario in the NCHPM crew/vessel specific performance targets. These can be based on absolute performance targets (e.g. for evacuation scenarios to complete evacuation within a prescribed time, such as IMO specified limits) or relative performance targets (e.g. time to complete a specific scenario in two different design models). In the latter case, the aim is to compare two options for the vessel's configuration and identify ways in which performance can be improved with each design iteration. For example, one relative performance target

could be to minimise the time for a damage control party to assemble and reach the scene of the incident. The evaluation of the overall vessel design can then be performed using a Performance Function (PF) that combines individual results from each of the scenarios with each scenario being assigned weights dependent on vessel type and role. The final result of the Performance Function is the Vessel Performance factor as described in Section 3.6.1 (page 80).

To address all of these requirements the maritimeEXODUS software had to be improved a range of enhancements. These include the development of additional output parameters to measure performance in the scenarios and required for the definition of the HPM and additional modelling capabilities, necessary to perform the identified circulation scenarios. The latter involved adding new algorithms and options to the itinerary functionality already available within maritimeEXODUS so that the requirements developed could be accommodated. In addition, it was necessary to enhance the decision-making capabilities of the automata to accommodate the complex logic required to simulate the selected scenarios.

## Appendix C - The connectivity-items library

This Appendix details the characteristics, definitions and implementation of the Human Factors Features introduced as part of this research in a standard library (or database) of Equipment Items (EIs) that can be directly imported and used in PARAMARINE-SURFCON. EIs' description, instructions and guidance on how to allow their correct modelling, use and consistency (i.e. how to modify EIs' definition to accommodate design specific needs) are also included in this Section to give a more holistic overview of the advantages the use of the EI library can offer.

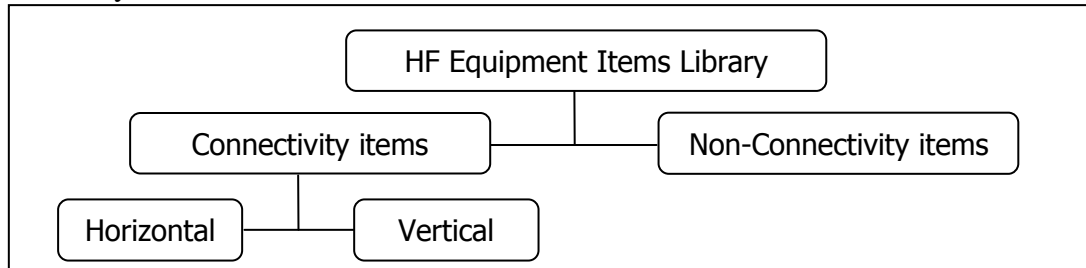


Figure C-1 - Equipment Items' classification diagram.

As illustrated in Figure C-1, there are two main types of items in the library: connectivity and non-connectivity items. Connectivity items define the logical connection between two Design Building Blocks (e.g. doors and ladders): their definition incorporates information on the nature of such a connection and represent its characteristics in numeric format (e.g. time to operate and delay in using the connection). Non-connectivity items have a standard (and simple) definition and are associated with a single Design Building Block (e.g. damage control and fire fighting locker). Particular attention has been given to connectivity items as their use is seen as an important innovation introduced by this research.

As described in Section 3.4, the connectivity items add to the model description information which is essential to conducting personnel movement simulation. Once all connections have been implemented in the model description, they allow the automatic generation of a logical network of interlinked connections, which will then be used in the simulation software to establish all possible routes available for the movement of the simulated crew. Connectivity items can be classified into two types: horizontal and vertical. Horizontal connectivity items connect two building blocks located on the same deck while vertical connectivity items link building blocks situated on different decks. Vertical connectivity items can also be used to logically connect more than two building blocks (e.g. lifts, stairs), while each horizontal connectivity item is limited to connecting two building blocks. The standard definition of each item included in the library is of general applicability, but can also be customised by the designer.

The SURFCON Equipment Items defined as part of this research, are divided into classes and each class is described in this Appendix. For each class there is a description and table illustrating the different steps and visual representations of a representative EI during the process of exporting its SURFCON description into maritimeEXODUS. The first two columns show respectively PARAMARINE's hierarchical tree-pane view relevant to the EIs' definition and a screenshot of the

graphics pane showing the EI visualisation. The third column illustrates the relevant representation in the output .DXF deck plan file (and therefore in the 2D general arrangements drawings) whilst the last column features the EI representation in maritimeEXODUS. The translation of the associated code is automatically resolved by the bespoke interface software developed as part of this research.

The Classes the SURFCON Equipment Items are divided in are the following:

- EI Class 1) Standard Doors and Watertight Doors
- EI Class 2) External WTD doors
- EI Class 3) Sliding Doors
- EI Class 4) Double Doors
- EI Class 5) Internal and External Stairs
- EI Class 6) Vertical Ladders
- EI Class 7) Horizontal Hatch with Vertical Ladder
- EI Class 8) Emergency Exit with Vertical Ladder
- EI Class 9) Fight EIs Lockers, Valves, and other significant waypoints
- EI Class 10) Hangar Door
- EI Class 11) Arched openings
- EI Class 12) User defined waypoints

Each of these Classes is described below.

### **EI Class 1) Standard Doors and Watertight Doors**

Standard Doors (referred to as Doors) and Watertight Doors (WTD) represent two main categories of horizontal connectivity items. These two classes of equipment items have been defined to represent respectively standard pivoting doors and standard watertight doors. Each class consists of four different equipment items, as shown in Table C-1, accommodating for the peculiar characteristics of the class. Each equipment item has a similar visible geometry (see Table C-2) and is defined according to a number of parameters included in its description.

The “Standard Door” class	The “Standard WTD” class
1) Standard Door, Push, Clockwise,	1) Standard WTD, Push, Clockwise,
2) Standard Door, Pull, Clockwise,	2) Standard WTD, Pull, Clockwise,
3) Standard Door, Push, Anticlockwise,	3) Standard WTD, Push, Anticlockwise,
4) Standard Door, Pull, Anticlockwise.	4) Standard WTD, Pull, Anticlockwise.

Table C-1 - Equipment Item entities defined in the door classes.

The main distinction between watertight and non-watertight doors is in the different values of the “Door Delay” parameter (i.e. the time required to open and close the door).

Each Equipment Item is placed in the design using the “Equipment Instance” PARAMARINE object and positioned by means of its “datum point” coordinates. The equipment item’s datum point X and Y coordinates are positioned by defining an offset from the datum point of the relevant Building Block (BB),



while the Z coordinate refers to the deck the EI (and the connected BBs) is located on. The relevant Building Block to be used and associated with an EI definition is indicated in the item's description by means of the direction in which the door opens; the convention used is that a "Pull" door should open *into* the Building Block it should be linked to. This represents an intuitive operation and a solution that allows the design flexibility to be maintained unaffected since every equipment item will remain associated with its respective building block in every model modification.

To facilitate the designer in performing the operation of assigning the correct BB to each EI, a visual anchor (see Figure 3.4.3, page 68) was introduced to indicate the correct BB the door definition should be associated with. This visual anchor is visible if a predefined variable in the library is set to be one<sup>32</sup>. If, alternatively, the value of this variable is set to zero, such visual indicator is turned off (i.e. being invisible to the user) in PARAMARINE's graphics pane. This proved to be a very useful feature, for example, in preventing the visual anchor to be visible when 2D drawings of the general arrangements need to be produced.

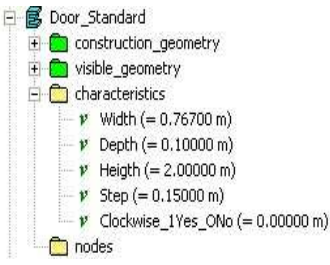
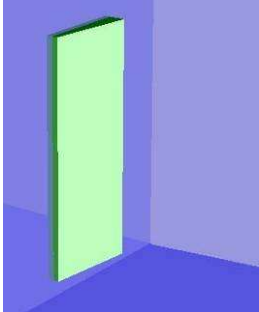
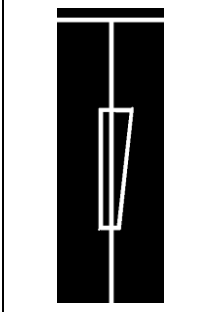
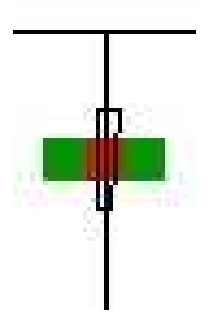
			
Equipment Item Definition	SURFCON / PARAMARINE	DXF	maritimeEXODUS

Table C-2 - Standard Door and WTD description and illustration.

The output in maritimeEXODUS, illustrated in the last column of Table C-2 uses a "Door Node" (in red) and two "Free Space Nodes" (in green) on either side of the door node. The properties associated with the door node are outlined in Table C-3, while the green nodes possess very basic information and their characteristics are shown in Table C-4.

From the SURFCON spatial model:	From the Scenario Setup table:
<ul style="list-style-type: none"> <li>• Type of Door</li> <li>• Title (Name Tag)</li> <li>• Label</li> <li>• Direction</li> <li>• Location (coordinates: X, Y)</li> <li>• WinID (vertical position: Z)</li> </ul>	<ul style="list-style-type: none"> <li>• Potential</li> <li>• Obstacle</li> <li>• Open/Close condition</li> <li>• Active/Inactive condition</li> <li>• Door Delay (min and max)</li> </ul>

Table C-3 - Door Node general parameters.

<sup>32</sup> The variable's name is "ID\_Node\_Visibility\_Control.characteristics.Visibility\_Switch".

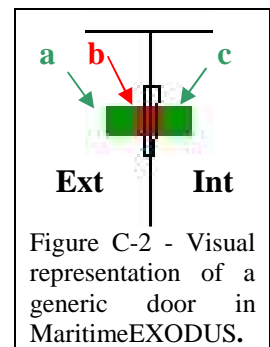
From the SURFCON spatial model:
<ul style="list-style-type: none"> <li>• Title (Name Tag)</li> <li>• Location (coordinates: X, Y)</li> <li>• WinID (vertical position: Z)</li> </ul>

Table C-4 - Free Space Node properties.

The information and parameters outlined in Table C-3 and Table C-4 are saved in the PARAMARINE design file (i.e. the '.design' file) and constitute part of the ship model description. These data are then translated by the developed interface software and transferred into maritimeEXODUS through the '.NMTA' file as described in Section 3.6. The UCL spreadsheet-based prototype interface software transfers all EIs characteristics that are essential to perform the selected simulations, optimising the file size and, consequently, the time required to compute the syntax translation.

Further investigation into the usability of the system and in the effectiveness of the presentation of the simulation results to the designer is needed to determine whether the fire zone name of each EI should be included in their description or not. This would allow a better description of the ship's fire compartmentation and would allow the designer to more easily and intuitively explore additional aspects personnel movement simulation relevant to the design under investigation.

One of the important new features introduced as part of this research and implemented in the prototype interface software is the capability to automatically retain the name of the compartment associated with the EI. This allows a more intuitive set-up and investigation of the simulation results and also resolves the problem of not having unique identifiers for each of the EI (un-ambiguity in the definition of model components). Retaining the compartment name was achieved using the "Title" property of the nodes used to describe equipment items in the maritimeEXODUS environment. The three nodes in Figure C-2 (i.e. a, b and c), for example, represent respectively the "Free Space Node" (a) in the external compartment (Ext) (e.g. a corridor), the Door Node (b) and the "Free Space Node" (c) associated to the internal compartment (Int). Each "green node" associated to the Building Block it is contained in is automatically assigned the compartment's name according to its definition in the SURFCON hierarchy. The flexibility of the SURFCON Equipment Item definitions, together with the capabilities of the interface software, allow the designer to define different types of doors simply by creating new equipment items with different characteristics and new names associated with their description.



Another important modification to how maritimeEXODUS represents the SURFCON model and introduced while the candidate was developing the interface software, deals with the definition of the Free Space Nodes adjacent to the door and, in particular, with their distance from it. Usually, nodes are automatically positioned in maritimeEXODUS according to a predefined grid in which its environment is discretised into. This pre-defined grid of nodes constituted a considerable obstacle to performing the automatic nodal flooding operation

developed at UoG (see Section 3.10), especially when considering the particularly confined nature of some spaces in a naval vessel. The main obstacle was the 0.5m distance between each node in the grid, which, in several instances, resulted in the impossibility for the software to place a node in a passageway. To overcome this problem, the candidate developed a script which defines the Free Space Nodes on either side of the Door Node as being placed at a separation distance of 0.1m from the Door Node itself. The effects of this modification are shown in Table C-5, while its effects on the node flooding operation have been described in Section 3.10.

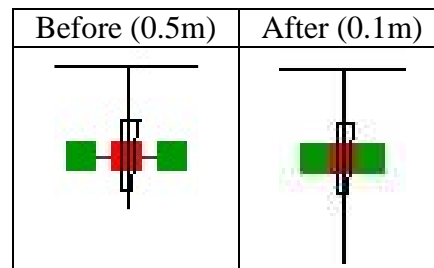


Table C-5 - Comparison of nodal arrangement.

## EI Class 2) External WTD doors

These equipment items are defined in an equivalent way to the equipment items described in Class 1. The main difference is that the visual anchor for the designer will be placed inside the internal compartment the EI is associated with.

As a consequence, the definition of the External WTD door will be referred to the datum point of that building block and will be associated with its name.

## EI Class 3) Sliding Doors

This class of equipment items was introduced in order to model sliding doors. The Sliding Door Class contains four different equipment items as described in Table C-6.

The “Sliding Door” class
1) Sliding Door, Sliding internally to the left, 2) Sliding Door, Sliding internally to the right, 3) Sliding Door, Sliding externally to the left, 4) Sliding Door, Sliding externally to the right.

Table C-6 - Entities in the sliding door EI class.

The same rules and procedures used for Class 1 EIs ought to be used when choosing which type of door to introduce in the model and how to connect it to existing Building Blocks. As far as the maritimeEXODUS representation is concerned, the main variation in the modelling of this type of doors will reside in the associated “Door Delay” property (i.e. time required to open and close the door).

The description and visualisation of this EI is shown in Table C-7.

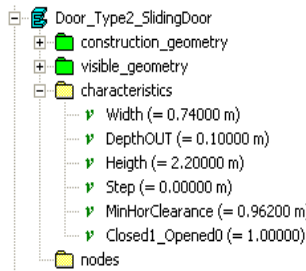
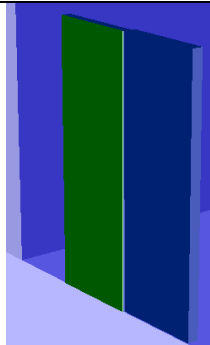
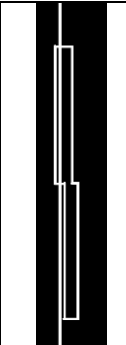
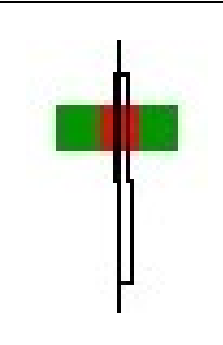
 <pre> Door_Type2_SlidingDoor ├── construction_geometry ├── visible_geometry ├── characteristics │   ├── Width (= 0.74000 m) │   ├── DepthOUT (= 0.10000 m) │   ├── Height (= 2.20000 m) │   ├── Step (= 0.00000 m) │   ├── MinHorClearance (= 0.96200 m) │   └── Closed1_Opened0 (= 1.00000) └── nodes         </pre>			
Equipment Item Definition	SURFCON / PARAMARINE	DXF	maritimeEXODUS

Table C-7 - Sliding door description and illustration.

#### EI Class 4) Double Doors

This class was defined given the necessity of introducing double doors in the model. After a detailed investigation on the issues relevant to this type of doors the following representation seemed to be the most suitable for their correct modelling. This class contains two different equipment items, as shown in Table C-8.

The “Double Door” class
1) Double Door, Push, 2) Double Door, Pull.

Table C-8 - Entities in the double door class.

The same rules and procedures described in Class 1 apply when choosing which of the two items to introduce in the model. As far as the maritimeEXODUS model is concerned, the linking software output is illustrated in the last column of Table C-9.

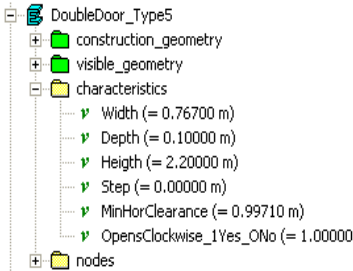
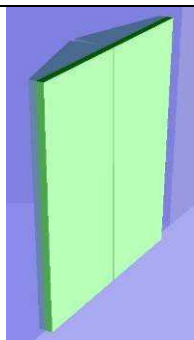
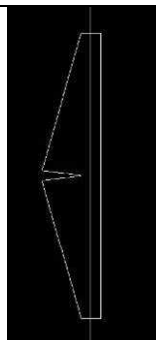
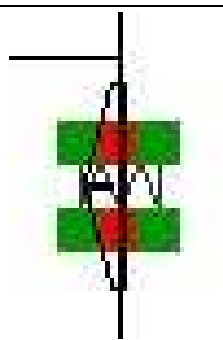
 <pre> DoubleDoor_Type5 ├── construction_geometry ├── visible_geometry ├── characteristics │   ├── Width (= 0.76700 m) │   ├── Depth (= 0.10000 m) │   ├── Height (= 2.20000 m) │   ├── Step (= 0.00000 m) │   ├── MinHorClearance (= 0.99710 m) │   └── OpensClockwise_1Yes_ONo (= 1.00000) └── nodes         </pre>			
Equipment Item Definition	SURFCON / PARAMARINE	DXF	maritimeEXODUS

Table C-9 - Double door description and illustration.

In this case there are two red nodes representing respectively each half of the double door and four green Free Space Nodes retaining connectivity data.

As previously described for the other door types, the two internal Free Space Nodes will be titled with the name of the compartment the door is linked to. It should be noted that the linking software (although in its prototype version) correctly defines ten separate arc connections between the six nodes.

### **EI Class 5) Internal and External Stairs**

The first class of equipment items modelling vertical connectivity between decks is stairs. This class contains two equipment items as shown in Table C-10.

The "Stair" class
1) Internal stair, 2) External stair.

Table C-10 - Entities in the stair class.

The definition of these equipment items assigned to vertically connect Building Blocks is generic and flexible. As shown by the screenshot in the first column of Table C-11, a number of different variables have been introduced in order to give the designer complete autonomy and flexibility in customising their description. The SURFCON user can control every parameter of the equipment item definition, adapting it to the design needs.

In maritimeEXODUS, a staircase is represented by a series of nodes with specific characteristics which are placed in the space between two decks; this series of nodes is then connected with two nodes, each on the two decks the stair links together. The position of the nodes, the definition of their characteristics and connections was previously carried out manually by the user, but the candidate programmed a number of additional algorithms into the prototype interface software and added some additional parameters to the SURFCON object to allow a consistent and automated generation and translation of these objects.

The first innovation introduced is a bounding box: a prism containing all the elements of the stair. This prevents the maritimeEXODUS automatic node-flooding operation from generating free space nodes in non-realistic positions (i.e. under the stairs and on the deck above, where the stair opening is). Moreover this bounding box, in maritimeEXODUS, will contain the eight nodes representing the stair steps; this will avoid the generation of arcs connecting steps and free space nodes during the automatic node-flood operation (ANFL, see Section 3.10).

The second modification regarded the visual representation of stairs within maritimeEXODUS. Stairs were usually manually placed in a separated position from the visual display of the deck geometry, in the empty space between the maritimeEXODUS window limits and those of the deck geometry itself.

In order to avoid any possible inconsistency and aiming for the complete automation of the data transfer process, this procedure has been changed and the nodes representing the stairs are now contained within the deck geometry (as shown in the last column of Table C-11). Stairs are automatically placed into maritimeEXODUS' model by the prototype translation software developed by

the candidate and via the .NMTA file. The first and the last nodes (i.e. the “landing nodes”: free space nodes on the two decks connected by the stair) are placed respectively on the deck where the stair is defined (i.e. starting deck - lower deck) and on the deck above (unless otherwise specified by the designer). The nodes representing the stairs’ steps are placed in within the bounding box limits, between decks and on the lower deck.

The third innovation introduced by the candidate is that the height of the stair can be defined in the equipment item definition rather than in the equipment instance. For this reason, in the equipment library for accessibility items, there will be a definition for each stair item connecting two different decks as shown in the hierarchy in Figure C-3.

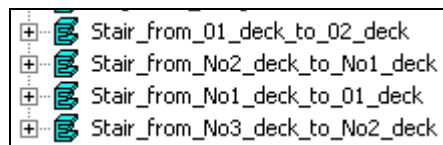


Figure C-3 - Customised definition of different stair types.

External ladders can also be defined and used in a similar way. The main difference in the library entry for this type of stairs is that the Free Space Nodes at either end of the stair take the name of the deck they are placed on, rather than that of a Building Block (since they are not connecting any). This is an important logical difference that is automatically taken into account and resolved by the translation software developed by the candidate. Table C-11 shows the stair vertical equipment item definition and visualisation.

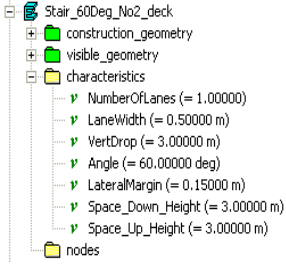
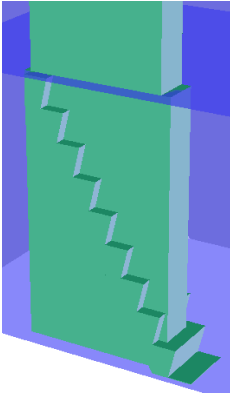
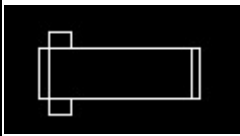
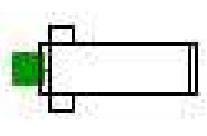

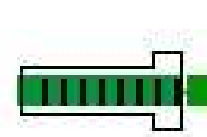
 <p>Stair_60Deg_No2_deck</p> <ul style="list-style-type: none"> <li>construction_geometry</li> <li>visible_geometry</li> <li>characteristics <ul style="list-style-type: none"> <li>NumberOfLanes (= 1.00000)</li> <li>LaneWidth (= 0.50000 m)</li> <li>VertDrop (= 3.00000 m)</li> <li>Angle (= 60.00000 deg)</li> <li>LateralMargin (= 0.15000 m)</li> <li>Space_Down_Height (= 3.00000 m)</li> <li>Space_Up_Height (= 3.00000 m)</li> </ul> </li> <li>nodes</li> </ul>				UPPER DECK
				LOWER DECK
Equipment Item Definition	SURFCON / PARAMARINE	DXF	maritimeEXODUS	

Table C-11 - Stairs description and representation (bounding box shown)

As for the other equipment items, the stair definition needs to be placed in the design using the Equipment Instance object and positioned by means of its “datum point” coordinates. The equipment item’s datum point coordinate need to be defined referring to the datum point of the Building Block the internal stair originates from. This is not necessary in the case of external stairs definition: the datum point coordinates can be inputted as referred to any building block in the design or as absolute numbers since the nodes, as previously described, are automatically assigned the name of the decks they are placed on.

For internal stairs, the automatic translation from the .KCL to the .NMTA syntax automatically resolves the reference to the Building Blocks embedded in the definition of the datum point coordinates and this allows the retention of the compartment and stair names, which are then used to name the nodes in maritimeEXODUS. The first node will inherit name of the compartment the internal stair starts from while the last node will have no title (or a dummy one). Each one of the steps is labelled with the SURFCON title associated with stair followed with a progressive number: from 1 (lowest step) to, typically, 8 (highest step).

The number of steps in a stair is automatically calculated based on the deck height and on ergonomic rules specifying the limits for step dimensions, vertical drop and horizontal gap (or overlap), but can be also manually defined by the designer should this need arise.

Internal and External stairs differ as they are processed separately in the linking software. The main difference is that for external stairs the first nodes title will be the name associated in SURFCON with the lower deck, whilst the last nodes title will be the upper decks name. In a consistent manner, all the vertical connectivity equipment items defined in the following Classes are referred to the horizontal datum point coordinates (i.e. X and Y coordinates) that specify the position the building block they originate from (i.e. the lower one). The vertical coordinate (i.e. the coordinate along the Z axis) will be referred to the deck the item originates from. In the case of external items, the consideration of the X and Y coordinate as a condition for its definition is irrelevant, in these cases, just the Z coordinate is used to inherit the names of the decks.

### **EI Class 6) Vertical Ladders**

This class of equipment items has been defined in order to represent Internal and External Vertical Ladders. The two elements in the class are shown in Table C-12.

The “ Vertical Ladders ” class
1) Internal Vertical Ladder, 2) External Vertical Ladder.

Table C-12 - Entities in the Vertical ladder class.

These vertical connectivity items are defined in SURFCON and placed in the model by locating the datum point on the lowest deck the ladder reaches (the same vertical ladder can connect multiple decks). The SURFCON / PARAMARINE visualisation of a ladder is shown in the second column of Table C-13.

This visible geometry has been associated to the equipment item for three main reasons; firstly in order to aid the designer in placing it correctly into the model, secondly to graphically indicate the position of the ladder in the PARAMARINE three-dimensional graphics pane, the .DXF drawing and, therefore, in the maritimeEXODUS interface, and thirdly to prevent the node flooding operation (see Section 3.10) from automatically connecting all the surrounding nodes to the ones defining the ladder.

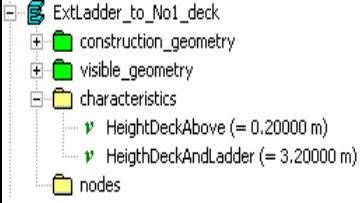
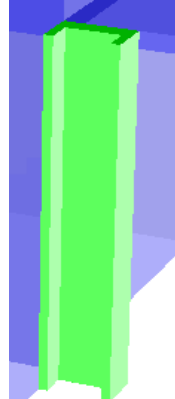
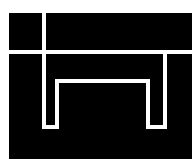
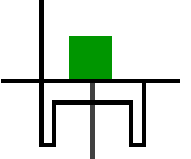
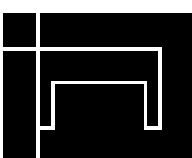
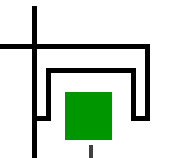
				UPPER DECK
				LOWER DECK
Equipment Item Definition	SURFCON / PARAMARINE	DXF	maritimeEXODUS	

Table C-13 - Vertical adder class: description and visual representation.

In Table C-13, the node on the upper deck is placed on the highest deck the ladder reaches, with this node inheriting the name of the deck it is on. In the case of an external vertical ladder the node on the lower deck will retain the name of the deck it is placed on. The Transit Node is titled according to the SURFCON name corresponding to the equipment instance. The main difference between internal and external ladders lies in the position of the node on the upper deck and in the names the nodes are labelled with. The prototype software is flexible enough to incorporate other specific differentiations introduced by the designer.

In maritimeEXODUS a vertical ladder is made from three different elements: the “ladder transit node” (shown in the image on the right) and two free Space Nodes connected to it. Usually, the “transit node” is manually placed by the user on the lower deck, but separate from the deck geometry; typically in the empty space between the maritimeEXODUS window limits and those of the geometry itself. To reproduce this solution, the translating software automatically positions this element using a similar philosophy: it places the Ladder Node (i.e. the Transit Node) on the lower border of the design bounding box, as shown in Figure C-4.

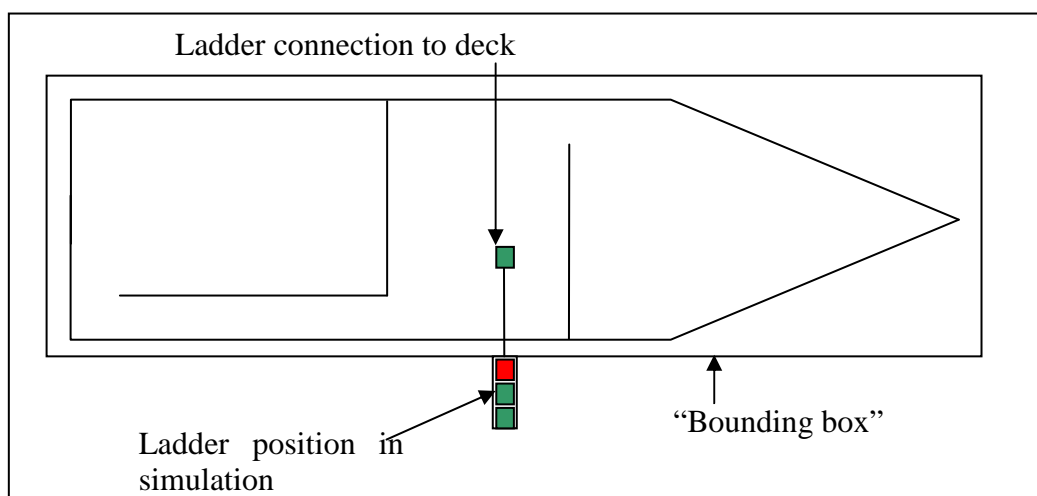


Figure C-4 - The bounding box concept, used to locate ladders in the simulation space.



### EI Class 7) Horizontal Hatch with Vertical Ladder

After having investigated a number of different solutions for the proper modelling and translation of horizontal hatches and emergency exits, the candidate eventually developed the description of horizontal hatches connected with vertical ladders as described in this section and that of emergency exits (escape routes) connected with vertical ladders as described in the next section (i.e. EI Class 8), page 254).

In maritimeEXODUS a horizontal hatch is represented using an Internal Exit Node (the red node in Table C-14). As a ladder is always linked to a horizontal hatch, this was adopted as the standard definition for this class, however, it is very simple to incorporate in the model other specified variations as needed by the designer. The visible geometry associated with this equipment item utilises the same reasoning as that used for the vertical ladder item (see EI Class 6). The Ladder Transit Node position is calculated from the coordinates of the datum point of the equipment item instance and placed on the external limits of the design bounding box (as shown in Figure C-4).

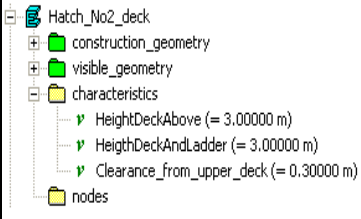
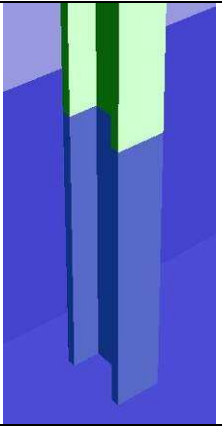
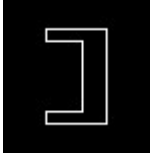
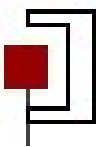
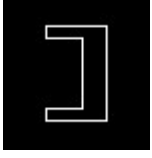
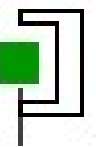
				UPPER DECK
				LOWER DECK
Equipment Item Definition	SURFCON/PARAMARINE	DXF	maritimeEXODUS	

Table C-14 - Hatch with ladder description and representation.

### EI Class 8) Emergency Exit with Vertical Ladder

This class of entities has been defined according to the same specifications used for normal horizontal hatches. The modification to the visible geometry associated with the equipment items in this class is shown in Table C-15 and has been developed to be consistent with the graphical representation in the provided general arrangement drawings. Specifically, this means that the upper deck visualisation of the emergency hatch in the DXF file is not present: emergency hatches are normally flat and levelled with the deck floor. This means that personnel can walk over the emergency hatch just like on any other part of the deck (unless, of course, if the hatch is open). The simple solution adopted by the candidate allows the simulation software to accommodate these properties.

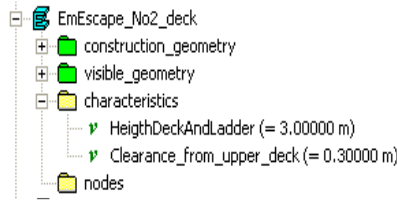
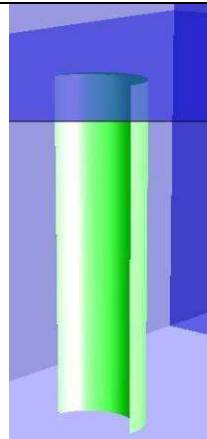
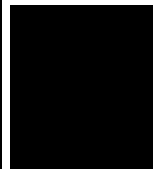
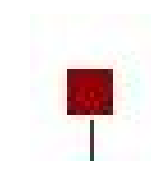

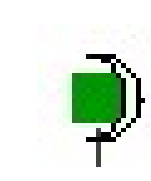
 <pre> EmEscape_No2_deck ├── construction_geometry ├── visible_geometry ├── characteristics │   ├── HeightDeckAndLadder (= 3.00000 m) │   └── Clearance_from_upper_deck (= 0.30000 m) └── nodes         </pre>				UPPER DECK
				LOWER DECK
Equipment Item Definition	SURFCON/PARAMARINE	DXF	maritimeEXODUS	

Table C-15 - Escape hatch with ladder: description and representation.

### **EI Class 9)    Fight EIs Lockers, Valves, and other significant waypoints**

This class of Equipment Items is made of “non connectivity items” i.e. equipment instances not used by the software to connect Building Blocks. Rather, the EIs in this class are used in the simulation procedure and setup tables (see Section 5.3.2) to indicate target points (i.e. locations and/or objects the simulated crew needs to reach to perform certain operations). As discussed in Section 3.6, to correctly define the operational procedures relevant to a specific scenario, a number of significant waypoints may need to be used. These can be, for example, main or auxiliary engines, life rafts and armament items.

These items are already defined and place in an early stage design model of a vessel, therefore there is no additional effort required by the designer to include them in the simulated scenario. In turn, some scenarios might require the addition of several other minor elements (e.g. lockers, valves, electric panels, switchboards) which are not normally modelled in early design stages. All these additional objects will need to be introduced in the SURFCON design as equipment items and included in the scenario procedure description; in turn, they will be seamlessly translated and transferred over to the simulation software and included in the simulation, just like happens for all other EIs described in the previous classes.

The EIs in this class have very few characteristic associated with their definition and can be represented in a very simple way in the simulation software environment. As shown in Table C-16, entities such as general Fight Equipment Items, can be created within maritimeEXODUS by importing their definition from the models available in the UCL DRC library of Fight Equipment Items (developed as part of previous research programmes and academic courses) into the SURFCON model and then running the interface software.

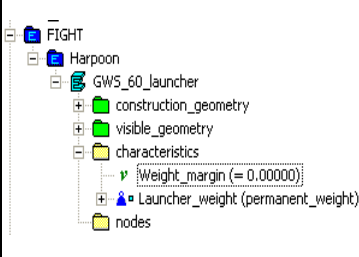
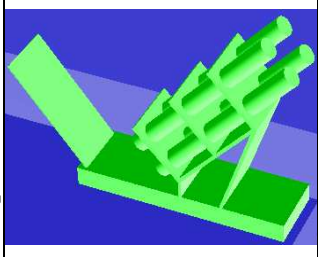
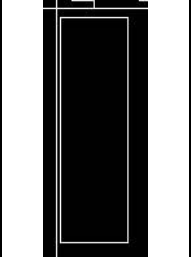
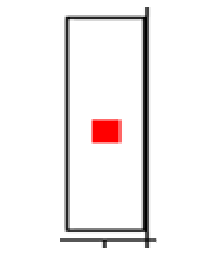
 <pre> FIGHT ├── Harpoon │   ├── GWS_60_launcher │   │   ├── construction_geometry │   │   ├── visible_geometry │   │   └── characteristics │   │       ├── [Weight_margin (= 0.00000)] │   │       └── Launcher_weight (permanent_weight) │   └── nodes </pre>			
Equipment Item Definition	SURFCON/PARAMARINE	DXF	maritimeEXODUS

Table C-16 - Fight equipment items: description and representation.

The software developed by the candidate is sufficiently flexible to be able to accommodate and translate the definition of any equipment item that can be defined in SURFCON. The solution adopted to accommodate this vast collection of varied equipment items in maritimeEXODUS is to represent each item by its outer geometry contour and a maritimeEXODUS “Exit Node” placed within the object’s geometry footprint. The node retains the name of the equipment item defined in SURFCON and its main characteristics, while the geometry contour isolates the equipment item from the network of nodal connections (i.e. network of possible routes the simulated crew can use).

### EI Class 10) Hangar Door

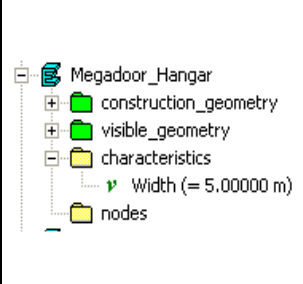
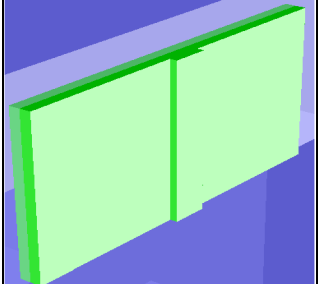
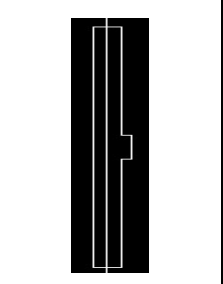
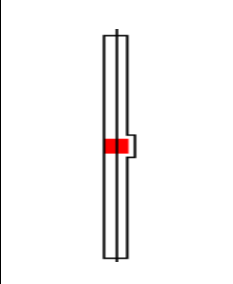
 <pre> Megadoor_Hangar ├── construction_geometry ├── visible_geometry ├── characteristics │   └── Width (= 5.00000 m) └── nodes </pre>			
Equipment Item Definition	SURFCON/PARAMARINE	DXF	maritimeEXODUS

Table C-17 - The hangar garage door: description and representations.

The hangar door is treated as a generic equipment item. Further investigation is needed to determine how to model it using the existing node types or if it requires the definition of a new maritimeEXODUS node type.

### EI Class 11) Arched openings

Arched openings are open connections between two spaces with no door. The only purpose of their introduction as equipment items is to create a logical connection between, for example, two separate but adjacent DBB that, in the mind of the designer are united in one element.

**EI Class 12) User defined waypoints**

To correctly define the operational procedures relevant to a specific scenario, a number of significant waypoints have to be used. Engines, life rafts and armament items will already be in place in an early stage design of a vessel, but some simulations might need the addition of several other elements (e.g. fire extinguishers, electric panels, switchboards, etc.). All these additional objects can be introduced in the SURFCON design as equipment items defined by the designer and, as any other equipment item, they will be transferred in the same way described in point 8 by the interface software.

As a consequence, this equipment items in this class do not have a standard geometry associated with their definition in SURFCON, therefore the user will have to check their correct implementation in maritimeEXODUS. This operation, however, needs to be done just once for each different item (and just if a different geometry is introduced), as the consistency of the interface software algorithms and procedures guarantees that the same item will be transferred across always in the same way.

## Appendix D - Type 22 Batch III Frigate data

### Type 22 Batch III Frigate data [Saunders 2008]

<b>Class and type:</b>	Type 22 Frigates, Batch III
<b>Ships in Class:</b>	F 99 HMS Cornwall - Commissioned 23 <sup>rd</sup> April 1988, F 85 HMS Cumberland - Commissioned 10 <sup>th</sup> June 1989, F 86 HMS Campbeltown - Commissioned 27 <sup>th</sup> May 1989, F 87 HMS Chatham - Commissioned 4 <sup>th</sup> May 1990.
<b>Builders:</b>	Yarrow Shipbuilders, Glasgow, Swan Hunter Shipbuilders, Wallsend-on-Tyne, Cammell Laird, Birkenhead.
<b>Laid Down:</b>	Between 1983 and 1986
<b>Launched:</b>	Between 1985 and 1988
<b>Displacement:</b>	5,300 tons
<b>Length (OA):</b>	485 ft 11 in ( 148.1 m )
<b>Beam:</b>	48 ft 6 in ( 14.8 m )
<b>Draft:</b>	21 ft ( 6.4 m )
<b>Armament:</b>	1 x 30 mm 7 barrelled Signaal / GE Gatling Goalkeeper CIWS 2 x 30 mm DES/MSI anti-aircraft guns in single mounts OR 2 x 20 mm Oerlikon anti-aircraft guns in single mounts 2 x Sea Wolf anti air launcher system (Total of 72 Sea Wolf missiles) 2 x Quad Harpoon 1C long range SSM missile launchers (total of 8 Harpoons) 2 x triple Stingray Magazine launched anti-submarine torpedo tubes (total of 36 torpedoes) 2 x 20 mm Oerlikon anti-aircraft guns in single mounts (GAM-BO1 guns) 1 x 4.5 inch (114 mm) Vickers 4.5" Mk 8 main gun NATO Seagnat Decoy Launchers
<b>Aircraft carried:</b>	2 x Lynx Mk.8 helicopters (but only 1 Lynx in peace time). <u>Armed with:</u> 4 x Sea Skua anti-ships missiles 2 x Sting Ray anti-submarine torpedoes 2 x Mk 11 depth charges
<b>Countermeasures:</b>	4 x Sea Gnat 6 barrelled launchers 1 x Towed torpedo decoy
<b>Propulsion:</b>	2 Rolls Royce Spey SM1A gas turbines 29500 hp (high speed) 2 Rolls Royce Tyne RM3C gas turbines 10680 hp (cruising)
<b>Maximum Speed:</b>	18 knots (33 km/h) cruise 30 knots (56 km/h) maximum
<b>Complement:</b>	250 (max. 301)
<b>Sensors:</b>	Type 1007 navigation radar Type 967 and 968 surveillance radar 2 x Type 911 Sea Wolf tracking radars UAT Electronic Surveillance System Type 2050 active sonar

Table D-1 - Type 22 Batch III Frigate data [Saunders 2008].

### Reference

[Saunders 2008] Saunders, Commodore, S., RN Editor, "Jane's Fighting Ships 2008-2009 Edition". Published by Jane's Information Group Sentinel House, 112th Edition Alexandria, USA, 2008.

**Low resolution general arrangement drawings (declassified).**

The general arrangement layout for the Type 22 Batch III Frigate [BMT DSL, 1996] is an unclassified version of the General Arrangement drawing [MoD, 2006]; given the confidential nature of the information contained in the GA, it was possible to include in this thesis only low resolution drawings also used as output of the simulation. The original GA drawings used, are stored in the UCL DRC database.

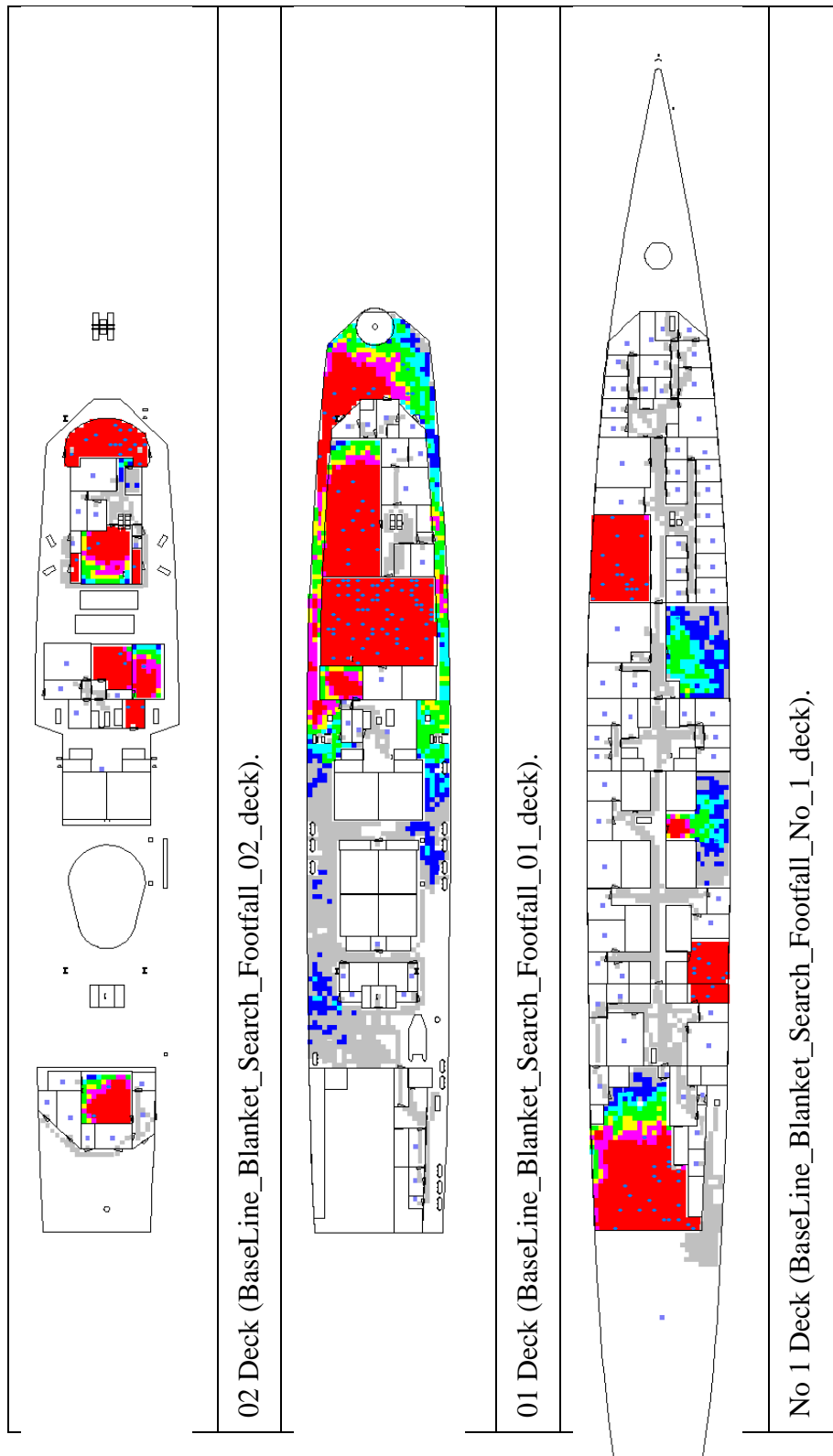


Table D-2 - Type 22 Batch III [part 1], General arrangement drawings (low resolution and density map for Blanket Search scenario)

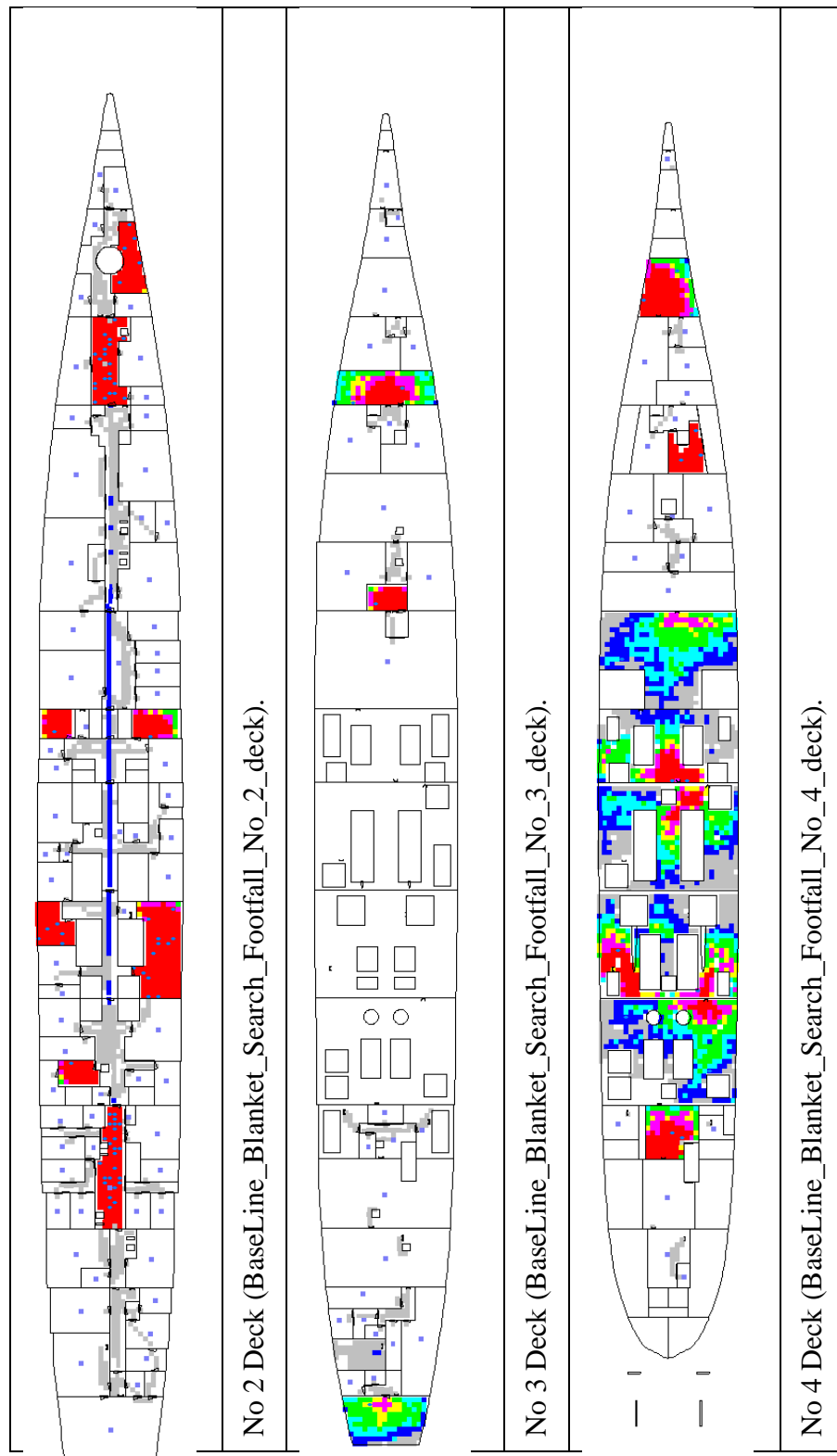


Table D-3 - Type 22 Batch III [part 2], General arrangement drawings (low resolution and density map for Blanket Search scenario)

### **Watch and Station Bill (W&SB).**

The watch and station bill (W&SB) is a document that outlines where every crew member's duty station is for any given evolution from normal cruising to full combat operations. The general format of a W&SB consists of a chart (or matrix) of the list of names of all personnel on board the ship, their rank, role, watch team and Functional Groups to which the member is assigned and the member's job responsibility and operating location during emergencies. All the parameters included in the W&SB are detailed in Appendix E, under point (5) - "Manning". The W&SB, was used to define the initial and final locations and activity of each crew member in each readiness state and ship evolution, as it contains all the procedural data and information required.

The STG Liaison Officer (Lt. Cdr. Boxall P.) was able to provide the a declassified version of the watch and station bill for a Type 22 Batch III RN Frigate and was able to assist in its interpretation by providing appropriate information and operational insights. This W&SB was obviously more detailed than would be available in a new initial design, as it was derived from the one used onboard of in-service units.

During this research (as mentioned in Section 3.4), some difficulties were experienced in obtaining sufficient data to generate a representative Watch and Station Bill (W&SB) for the baseline Type 22 Batch III design, because of the restricted nature of such information. This also highlighted a potential difficulty in achieving the integration of personnel movement simulation to the early stages of ship design, in that such information (which is the crucial to the generation of the scenarios to be simulated) might not be available for an entirely new configuration. This could cause difficulties in addressing the steps necessary to achieve a complete integration as described in Section 3.6 .

However, during a UCL MSc Ship Design Exercise, one study group composed of serving RN and CF personnel and MoD staff, tasked with designing a highly innovative trimaran unmanned vehicle carrier (UVX) with a very low manning requirement was able to generate, based on knowledge and experience a representative W&SB. This contained the rank and organisational structure (Functional Groups) and physical locations for each individual crew member in each readiness state, with their accommodation being marked on the General Arrangement but not assigned by individual. The time taken to generate this indicative but representative W&SB was given as around two hours. This was a highly relevant result for this research as it demonstrated the possibility of rapidly producing an indicative crew breakdown and W&SB in a very short time and entirely commensurate with the use of personnel movement simulation in concept ship design. This starting point was then used to initiate a discussion both within the MSc design group and with UCL staff and industry experts on the feasibility of the manning strategy adopted in the student design study. In particular, if PARAMARINE-SURFCON was used to generate the ship design model (using the standards specified by this research and included in the UCL DRC procedures) then it would have been possible to export the design definition, perform personnel movement simulations and feed the results back into the concept ship design process. This would then provide entirely new design capability for real concept studies as well as Post Graduate design studies.



Table D-4 (below) shows part of the W&SB developed and used in this research. Given the confidential nature of the information contained in the full W&SB, it was not possible to include the full matrix in this. The document is stored in the UCL DRC database.

		DEPT	RATE/rank	State 1	State 2	State 3	Emergency Stations	Cabin	Evacuation Watch	Functional Group
1	ID									
231	223	WE	PO(WEA)	EWO		OPS ROOM	WSB	SRs CCKLN1PO4	NEAREST 2ND STBD	Warfare (Fighting)
232	158	WE	LWEM(O)	FWD FRPP	WSB	HARPOON	FWD FRPP	JRs M.JRsmrs24	NEAREST 1ST STBD	Damage Control
233	102	WE	PO(WEA)	FWD Gyro		HARPOON	WSB	SRs CCHN2PO3	NEAREST 2ND PORT	Weapons Engineers (operators)
234	155	WE	PO(WEA)	FWD SIS		FWD SIS	WSB	SRs CCLN1CPO1	NEAREST 1ST STBD	Warfare (Fighting)
235	103	WE	LWEM(R)	FWD SIS		OPS ROOM	WSB	JRs M.JRsmrs18	NEAREST 2ND PORT	Weapons Engineers (operators)
236	157	WE	PO(WEA)	FWD TRACKER	FWD TRACKER	FWD TRACKER	WSB	SRs CCPN2CPO7	NEAREST 1ST STBD	Warfare (Fighting)
237	224	WE	PO(WEM)	FWD TRACKER	FWD TRACKER	FWD TRACKER	WSB	SRs CCKLN1PO4	NEAREST 2ND STBD	Warfare (Fighting)
238	104	WE	LWEM(O)	GOALKEEPER NOPS ROOM	OPS ROOM	OPS ROOM	WSB	JRs M.JRsmrs18	NEAREST 2ND PORT	Weapons Engineers (operators)
239	34	WE	PO(WEA)	GOALKEEPER Power Room	OPS ROOM	OPS ROOM	WSB	SRs CCMN2PO5	NEAREST 1ST PORT	Warfare (Fighting)
240	220	WE	CWEM	HQ1	HANGAR	REG OFF	HANGAR	SRs CCPN2CPO5	NEAREST 2ND STBD	Damage Control Organisation
241	221	WE	CWEM	MCO		MCO	MCO	SRs CCPN2CPO5	NEAREST 2ND STBD	Warfare (Fighting)
242	36	WE	PO(WEM)	MCO		SCOT	WSB	SRs CCMN2PO5	NEAREST 1ST PORT	Warfare (Fighting)
243	154	WE	PO(WEA)	OPS ANNEX	OPS ANNEX	OPS ANNEX	OPS ROOM	SRs CCPN2CPO7	NEAREST 1ST STBD	Warfare (Fighting)
244	32	WE	LTCDR	OPS ROOM	OPS ROOM	OPS ROOM	OPS ROOM	OCCGN1III13	NEAREST 1ST PORT	Damage Control Organisation
245	33	WE	LT	OPS ROOM	OPS ROOM	OPS ROOM	WSB	OCCHN1CLIII27	NEAREST 1ST PORT	Warfare (Fighting)
246	222	WE	CWEA	OPS ROOM	OPS ROOM	CTO	OPS ROOM	SRs CCPN2CPO5	NEAREST 2ND STBD	Warfare (Fighting)
247	38	WE	LWEA	OPS ROOM	OPS ANNEX	OPS ROOM ANN	WSB	JRs M.JRsmrs14	NEAREST 1ST PORT	Warfare (Fighting)
248	160	WE	LWEM(R)	OPS ROOM	OPS ROOM	OPS ROOM	WSB	JRs M.JRsmrs24	NEAREST 1ST STBD	Warfare (upper deck)
249	43	WE	WEA	OPS ROOM	WSB		WSB	JRs M.JRsmrs33	NEAREST 1ST PORT	Warfare (Fighting)
250	37	WE	PO(WEA)	SURV OFFICE			WSB	SRs CCPN2CPO9	NEAREST 1ST PORT	Warfare (Fighting)
251	156	WE	PO(WEA)	TAS STORE		HANGAR	WSB	SRs CCPN2CPO7	NEAREST 1ST STBD	Warfare (Fighting)
252	40	WE	LWEM(O)	TAS STORE	WSB	CANTEEN	WSB	JRs M.JRsmrs14	NEAREST 1ST PORT	Warfare (Fighting)
253	159	WE	LWEM(O)	TAS STORE	WSB	HANGAR	WSB	JRs M.JRsmrs24	NEAREST 1ST STBD	Warfare (Fighting)
254	100	WE	PO(WEM)	TELEX	TELEX	TELEX	WSB	SRs CCHN2PO3	NEAREST 1ST PORT	Warfare (Fighting)
255	153	WE	LT	WSB	OPS ROOM		HQ1	OCCEN1IASupOff2	NEAREST 2ND PORT	Weapons Engineers (operators)
256	98	WE	CCWEA	WSB	WSB	EMR	WSB	OCCJN1CLIII14	NEAREST 1ST STBD	Weapons Engineers (maintainers)
257	219	WE	CCWEA	WSB	WSB	EMR	WSB	OCCJN1CLII29	NEAREST 2ND PORT	Weapons Engineers (maintainers)
258	39	WE	LWEM(R)	WSB	WSB	OPS ROOM ANNEX	WSB	JRs M.JRsmrs14	NEAREST 1ST PORT	Warfare (Fighting)
259	106	WE	LWEM(R)	WSB	WSB	MCO	WSB	JRs M.JRsmrs18	NEAREST 2ND PORT	Weapons Engineers (maintainers)
260	226	WE	LWEM(O)	WSB	TELEX	TELEX	WSB	JRs M.JRsmrs33	NEAREST 2ND STBD	Weapons Engineers (maintainers)
261	107	WE	WEA	WSB	WSB		WSB	JRs M.JRsmrs37	NEAREST 2ND PORT	Weapons Engineers (maintainers)
262	161	WE	WEA	WSB	WSB			JRs M.JRsmrs37	NEAREST 1ST STBD	Weapons Engineers (maintainers)
263	227	WE	WEA	WSB	WSB		WSB	JRs M.JRsmrs39	NEAREST 2ND STBD	Weapons Engineers (maintainers)
264	0	CIV		None	None	None	None	None	NEAREST None	Civilians
265										

Table D-4 - Part of the W&amp;SB developed and used in the research.

## Appendix E - The prototype software interface

The research aim (see Section 1.2) was for the two primary software tools (PARAMARINE-SURFCON and maritimeEXODUS) to interface with each other and for them to be used to generate guidance, not only on design for evacuation but also design for enhanced operational effectiveness with regard to personnel issues.

Figure E-1 illustrates the high level procedure developed by the candidate for utilising the two software tools for the analysis of personnel movement in early stage design. The upper box shows the software tools used and the lower boxes show the operations undertaken in each of the software tools.

The software set used in this research consists of PARAMARINE–SURFCON for naval architecture modelling and assessment tasks, maritimeEXODUS for personnel movement simulation and the “interface software” to transfer the required information between PARAMARINE-SURFCON and maritimeEXODUS.

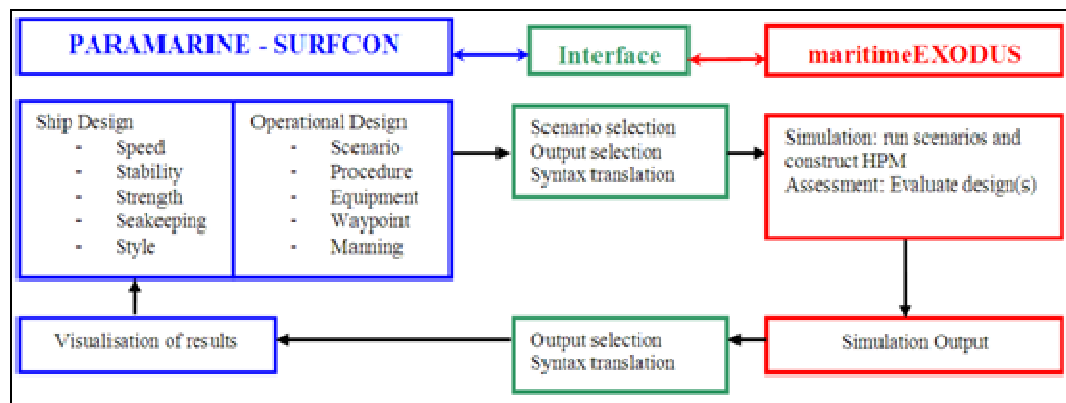


Figure E-1 - Flow procedure for personnel movement analysis using separate tools within the joint UCL (DRC) and UoG (FSEG) EPSRC project.

As mentioned in Section 3.7 no changes were made to the PARAMARINE-SURFCON software, instead, the integration of the software packages was accomplished by the use of the bespoke interface tools produced by the candidate and some modifications introduced to maritimeEXODUS. This approach had certain advantages, as the interface tools could be changed by the candidate to reflect the evolving needs of the research, allowing development and assessment of ship design models to be carried out with the interface tools at a very basic level of functionality, which could later be improved. The aim of this research was never that of developing a fully worked interface software, nor PARAMARINE-SURFCON and maritimeEXODUS were intended to be integrated into a single package. Instead, the objective was to achieve an integration of the two programs with a breadboard system that would allow investigating the important issues of procedural integration of personnel movement simulation and preliminary design.

The significance of the developments described in this appendix is that, if the described standards of definition of the geometry, connectivity and procedural data are adhered to, then the interface software developed by the candidate can be used to transfer the PARAMARINE-SURFCON model of any vessel, vehicle or building

to maritimeEXODUS (and to the other EXODUS packages e.g. airEXODUS and buildingEXODUS), to facilitate personnel movement simulation.

From the desired functionality outlined in Section 3.5, an equivalent software integration diagram can be drawn, as shown in Figure E-2. This flow diagram shows the types of information that must be transferred (numbered items) between the three software tools (PARAMARINE-SURFCON, maritimeEXODUS and the interface software), the file formats currently used to perform the transfer in the UCL prototype interface software (black text) and the steps required to process the information (orange letters). The flow chart of the logic of the interface software functionality in Figure E-1, shows the modular approach used in developing and running the interface software; each step of the process is explained below.

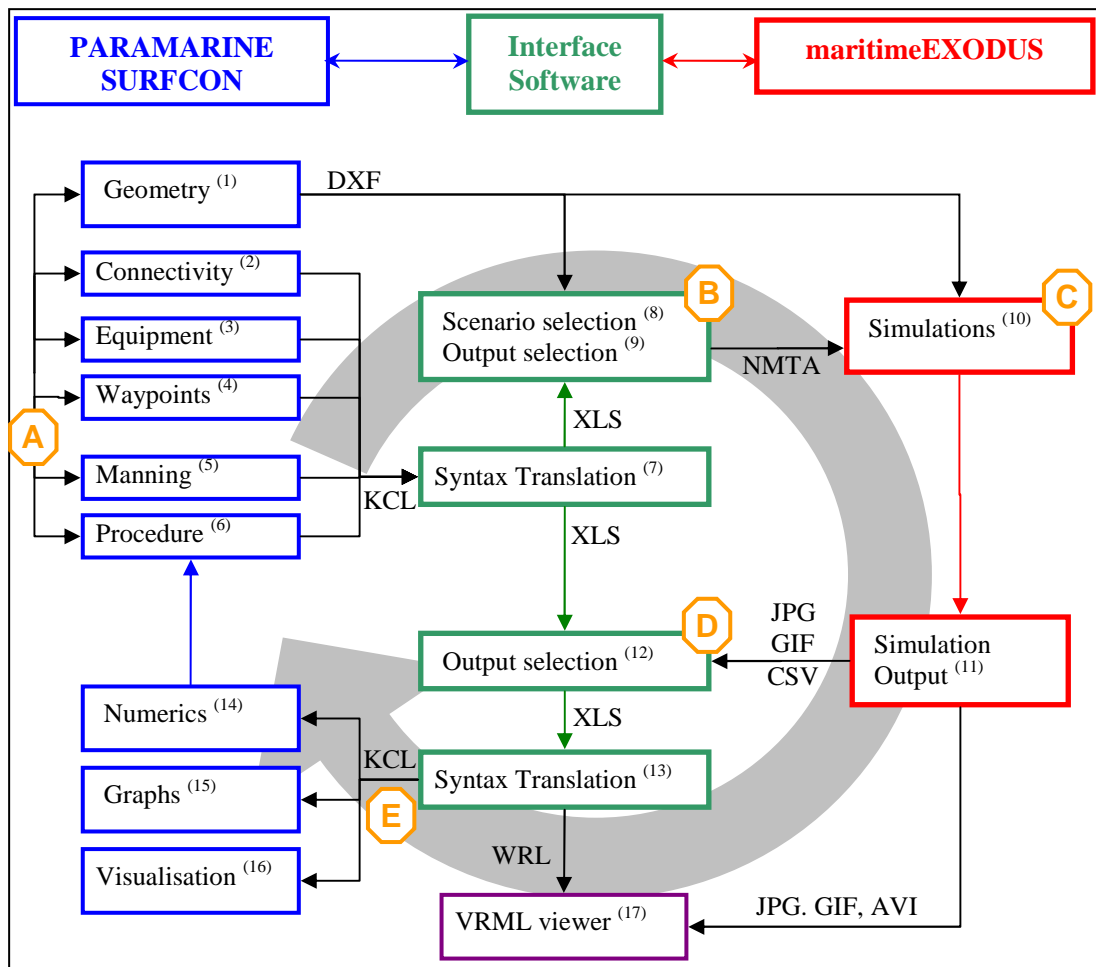


Figure E-2 - Flow chart of the logic of the technical implementation of the interface software functionality, showing its modular approach.

#### (A) Extracting information from the model.

This initial step collects all the information necessary to run the personnel movement simulation in maritimeEXODUS and compiles all necessary data in a single KCL file and in a set of DXF files, ready to be processed by the interface software. The information collected are described in more detail below (points 1 to 6).

## **(1) Geometry**

The main geometric data issue is the manner in which the ship is divided up into watertight and non-watertight spaces (internal arrangement). In maritimeEXODUS, each of the resulting areas, if accessible to personnel, would be described as a region containing a grid of interconnected nodes (i.e. nodal mesh).

The transfer of this data the candidate developed a dual approach utilising a DXF file and a KCL file. The DXF file containing a 2-dimensional line drawing of each deck and showing the internal boundaries, was generated in PARAMARINE-SURFCON and transferred to maritimeEXODUS without any editing as shown in Figure E-2. The KCL file was generated describing the Design Building Block hierarchy used to represent the ship design (as described below in points 2 to 6). The interface software is able to parse the complex KCL macro file and then resolve the locations of objects of interest (i.e. of the equipment items described in Appendix C). As any space, that is accessible to the crew, must have at least one door or hatch accessing it, it was possible to use these features to explicitly define the location, name and characteristics of each of the spaces in the ship, represented in maritimeEXODUS as regions of nodes, thus completing the geometric definition of the design.

The geometry of the SURFCON model is extracted from PARAMARINE as a series of bi-dimensional drawings in DXF format, obtained by intersecting the model at specific heights with horizontal planes. The height of the intersecting planes is automatically calculated by the interface software, based on the overall dimensions of the model. The output is a number of DXF files, each representing a single deck and the set of DXF files represents the general arrangements of the model. The candidate has devised a bespoke procedure which makes use of the existing SURFCON functionalities to produce the DXF files required by maritimeEXODUS.

The DXFs created by running this module will be used by maritimeEXODUS to automatically create a mesh of nodes representing the areas of the ship accessible to the simulated crew. However, the latest version of the automatic meshing algorithm produced by FSEG team at UoG following the requirement specification developed by the candidate, leads to sub-optimal meshing (as described in Section 3.10), with some narrow spaces not meshed. This is due to the way in which the algorithm is coded and able to interact with the model; the consequence is that un-meshed spaces limit the range of movements the simulated crew can perform, thereby affecting their performance and producing unrealistic results of the simulation. Therefore, the maritimeEXODUS' user has to review the automatically generated mesh to check for such errors and, where necessary, manually re-mesh the affected areas.

## **(2) Connectivity**

Connectivity information, mathematically describes how the functional spaces in the design are connected together. This module extracts the information from the model using the library of equipment items - connectivity items - dedicated to representing connections between SURFCON building blocks. This library was

developed by the candidate to represent all possible connections between functional spaces and all the items described in Appendix C. This module uses existing SURFCON functionality to produce its output.

In maritimeEXODUS, each space (represented by a region of nodes) must be connected to the others if it is to be accessible by the simulated crew in the simulations. The interface software produces an NMTA file to be used as input for the maritimeEXODUS Scenario Generator. The definition of these items in PARAMARINE-SURFCON utilised an existing functionality to produce an explicit representation of the connectivity feature within the spatial model, which could be resolved by the interface software to produce an absolute numerical representation of the location, orientation, type or each connectivity feature. This is an extensible format that allows additional entities to be created should the field of personnel movement simulation be further explored.

### (3) Equipment

Information about the location and dimensions of each equipment item are available in PARAMARINE and can be extracted using the existing SURFCON functionality. Equipment items of interest include access equipment (e.g. portable ladders) and functional equipment (e.g. machinery, weapons).

However, in addition to location and dimensions, maritimeEXODUS requires additional information to run its simulation engine. The candidate devised a standard procedure to associate each equipment item to these characteristics needed in order to run the simulation and this information are stored in a table in SURFCON.

The equipment items in the model can refer to a standard or custom defined set of characteristics pre-loaded in the Equipment Items library. These entries in the library include all the new characteristics required in order to run the simulation; these are the following:

- **“Equipment Number”** – a unique identification number for each equipment item;
- **“Equipment Name”** – the name of the equipment;
- **“Equipment Type”** – a code indicating the type of equipment (e.g. door, hatch, weapon, ladder, pump, valve);
- **“WT index”** – the watertight classification index (X, Y or Z) is associated with a specific status for each equipment item in each of the watertight conditions the ship is in (e.g. if the ship is in watertight Z, all watertight doors classified with Z as their “WT index” will be considered closed).
- **“Time to open”** and **“Time to close”** – the time, expressed in seconds, necessary to open/close a door or hatch (in the case of a weapon, these represents respectively, the time required to take it out of its stored position and load it and the time to put it back in its stored position after being used).
- **“Time to operate”** – the time, expressed in seconds, necessary to operate the equipment item. For example, in the case of a Watertight Door this parameter represents the time it takes to pass through it, while, in the case of a portable water pump, it represents the time it takes to activate it, once it has been transported to the correct location.

#### (4) Waypoints

Waypoints refer to the main functional spaces in the model and have a one-to-one correspondence with the geometry of the model (see point (1), above). All functional spaces are listed in this table of waypoints, whether they are going to be used by crew members in the simulated scenarios or not. This table links the functional spaces definition and characteristics to spatial model of the ship. .

Each waypoint represents a location in the vessel that the crew members can pass through during the evolutions under consideration or significant locations onboard where the simulated crew needs to get to (e.g. pumps, lockers, valves). The candidate has defined a number of a predefined set of significant locations in the ship that can be associated with the corresponding building blocks in the model. In addition, the designer has the possibility of defining new waypoints, as needed.

For example, the tabular entry for the “Communications Control Room” would be associated with the Design Building Block named (in the SURFCON hierarchy) “Concept.Synthesis.Design.Fight.Communication.RadioComms.Offices.CCR\_HP”. It is important to note that any SURFCON Equipment Item used in the model will automatically appear in the waypoints table, therefore, could be used as waypoint.

#### (5) Manning

This module is similar to the watch and station bill (W&SB, see also Appendix D) in that is a table defining all crew members’ operational roles on the ship, their physical characteristics and scenario specific location information for use in maritime EXODUS simulations. All the crew members are defined in SURFCON by a table containing the following characteristics:-

##### a) General Information

1. DEPARTMENT - The name of the department.
2. RATE - The rank of the crew member:
  - a. Officers: Captain (CAPT), Commander (CDR), Lieutenant Commander (LTCDR), Lieutenant (LT), Sub-Lieutenant (SLT), Midshipman (MSM),
  - b. Ratings (Non Commissioned Officers): Warrant Officer (WO, WO2), Chief Petty Officer (CPO), Petty Officer (PO),
  - c. Junior Rates: Leading Hand (LH), Air Engineering Mechanic (AEM), Operator Mechanic (OM), Marine Engineering Mechanic (MEM).
3. NAME - The name of the crew member (optional).
4. PQ (Number) - Personal identification number.
5. POS (Position on Ship) - The organisational role of each crew member.

##### b) Scenario Specific Location Information

Each of the parameters from 6 to 22 indicates a specific location on the ship where each crew member has to be when the ship is in a determined readiness state or undergoing the activity corresponding to the parameter’s name.

6. Action ON - Transitory phase when an action is announced as ready to be called.
7. Action OFF - Transitory phase when an action is completed and a new readiness is about to be called.
8. Defence - A general state of alertness where all crew members are awake and ready for action.

9. Cruising - When the ship is in normal cruising mode.
10. Duties - A general phase where all crew members are in their duty locations.
11. Boarding - When the crew or civilian personnel is boarding the ship.
12. SSD - Special Sea Duty (e.g. Special Sea Duty for man overboard)
13. RAS - Replenishment at Sea operations
14. SSEP - Standing Sea Emergency Party (e.g. Fire Fighting and Damage Control)
15. Shelter - When a Deployable Rapid Assembly Shelter (DRASH) needs to be set up, typically on the flight deck.
16. Awkward - Operation for countermeasures against attack from swimmers.
17. Emergency - General readiness state; complement is alerted and ready to follow instructions.
18. SPO - Ship Protection Organisation (anti-terrorist readiness state).
19. NBC - Nuclear, Biological and Chemical asset for the ship and crew.
20. MISC - Miscellaneous exercise; crew members not on duty or watch gather and are ready to operate according to instructions.
21. Cabin - Crew accommodation space.
22. Evacuation - Location where crew members have to assemble with their life-jackets, ready to abandon ship.

c) Organisational

23. Watch Team - The complement is divided in four watch teams (i.e. 1<sup>st</sup> port, 1<sup>st</sup> starboard, 2<sup>nd</sup> port, 2<sup>nd</sup> starboard) and in a group that has no specific watch duties – typically, senior officers and the Commander (i.e. DAYS).
24. Functional Group - Each crew member belongs to a functional group (i.e. First Aid, Warfare (i.e. OPS and Navigation), Warfare Support, Damage Control & Fire fighting, Electrical, Flight, Propulsion and Machinery). The capability of adding “civilian passengers” has been implemented with an additional functional group, namely “civil” for the purpose of simulating family day scenarios.

d) Physical and personal characteristics

25. Gender (M or F),
26. Age (numeric value),
27. Weight (kilograms),
28. Height (centimetres),
29. Health (a percentage from 100% - perfect health to 0% - deceased),
30. Knowledge (of the ship - expressed as a percentage) and
31. Reaction time (time it takes to start executing an order from the moment it was received).

Although this module developed by the candidate makes use of the existing SURFCON functionality, there is currently no link between the manning characteristics (described above) and the pre-defined “Personnel” demand / supply object used in early stage design, therefore all entries have to be manually compiled. If this missing link has no impact on running the simulations, it is a function that could be developed in the future, with the aim of further automating the procedure to run simulations and reduce the manual input required by designers.

## **(6) Operational Procedure**

This data concerns the watch and station bill (W&SB), which, by stating the location and activity of each crew member in each readiness state and ship evolution, contains all procedural data required for the personnel movement simulation to be executed. The generation and transfer of this data was found to be a key element of the definition of the ship design to simulate personnel movement.

By including this information in the PARAMARINE-SURFCON model the candidate was able to link W&SB locations (such as the bridge or Operations Room location) directly to the Design Building Block compartment definitions. The significance of this is that the spatial configuration of the design can readily be changed without the need to re-define the W&SB.

The operational procedure is a sequence of tasks to be performed by each crew member in each scenario to be simulated. The candidate has defined a table within SURFCON containing all the necessary information making use of existing SURFCON functionality.

The tasks are chosen from a predefined list of possible actions. The syntax associated with each actions has been created by the candidate, based on previous programming experience; the main feature is that all actions can be combined with each other in logic sequences. If necessary, the user can define new tasks using the same syntax or edit and customise the existing ones, adapting them to the specific needs of the scenarios to be simulated.

Tasks can also be assigned according to the crewmember characteristics; each set of tasks might be associated to single crew members or to an entire group of people (e.g. according to the Functional Group or Watch Team). To improve usability and ease of customising the operational procedure table, the candidate developed a function that allows tasks and sequence of tasks to be stored externally to SURFCON and defined via the interface software referencing the SURFCON spatial definition.

### **A new programming language**

In order to instruct maritimeEXODUS to simulate non-evacuation scenarios such as those in Table 2.6.1 (page 45) several new behaviours were required. These behaviours were defined by the candidate, introduced as part of the new programming language used to define the Operational Procedure and then implemented by the FSEG team in maritimeEXODUS. These most relevant new instructions are:

- Terminate
- Search
- Wait
- Give Command
- Receive Command
- Repeat
- Blanket search

Each one of these new behaviours will now be discussed.



**Terminate.** The first behaviour, ‘terminate’, is the most important behaviour that was implemented. This behaviour involves ‘terminating’ an individual’s involvement from the simulation. This action will tell the individual agent to stop. Their personal simulation clock will stop as to will all its’ other attributes (e.g. cumulative wait time), but maritimeEXODUS will leave the individual on the same node. This, in essence, is what makes maritimeEXODUS simulate circulation scenarios rather than evacuation ones. This action does not require any parameters, since the individual agent will simply stop in its location. There is also a variation on this command called ‘terminateMill’. With this command, when the individual automata terminates its actions and movement, will start to randomly move around the compartment it currently occupies. This means that they do not become an obstruction to others who may wish to get around them, for example if a person terminates next to a door, they will not block the doorway with this command.

**Search.** The second behaviour, ‘Search’, instructs an individual to enter a compartment where they will have a delay (calculated on the area of the compartment) which represents them searching the room. This action is particularly useful in the state 1 preparations scenario where it would represent the individual searching the compartment and securing any loose items. The action would also be useful in the ‘blanket search’ scenario where each crew member, for example, searches a compartment to determine the extent of damage that the vessel may have taken. This action has three parameters; ‘max delay’ and ‘min delay’ which defines a range of times that the delay could take and the third parameter is linked to the area of the compartment which the individual has to search.

**Wait.** The third behaviour, ‘Wait’ supports the ‘terminate’ action. With the ‘termination’ action, once the individual receives this command they will stop and remain on the same node until the end of the simulation, but if the ‘wait’ command is included in the individual’s itinerary then the individual will move randomly around the immediate vicinity of the node where they will finally terminate. This action ensures that an individual does not block the paths of other people who are still in the simulation and trying to get to a particular location, for example, prevents the individual from terminating in front of a door. This action requires no additional parameters.

**Give Order and Receive Command.** The fourth and fifth behaviours have been introduced to allow simulating the hierarchy on a naval ship. Both commands require the interaction (i.e. close nodal proximity in the simulation) of individual agents. An individual with the ‘Give order’ instruction programmed in its behaviour will go up to a certain node (i.e. a redirection node) and effectively give out instructions to the relevant agents (i.e. those programmed to receive commands) located within a catchment area (on average 6 nodes).

In maritimeEXODUS, the implementation of this new functionality has been programmed in a complex way: it is not the individual agent who assigns new itineraries (commands) to others, but rather the redirection node activated by the agent. Simulated crew members with the ‘Receive command’ will enter the catchment area of the above mentioned redirection node, wait there until the node is activated and then continue with executing the new itinerary as soon as the node has been activated.

A fundamental aspect of this new functionality defined by the candidate, is that each simulated crew member can (by default) give orders to others only if they are

of equal or lower rank (see 5) Manning → a) General Information → 2. Rate). This capability has been implemented within maritimeEXODUS and allows performing a more realistic simulation of the operations normally happening on a naval vessel.

**Repeat.** The sixth behaviour, ‘Repeat’, was designed for the patrol itinerary required for the “state 1 prep” scenario and allows a list of tasks to be carried out several times. The designer can specify the number of times the list is to repeated and this allows a significant simplification of the definition of the Operational Procedure table.

If the last task in the penultimate task in the itinerary is ‘terminate’ and the last task is ‘repeat’ and then the number of repeats is set to a high number such as 9999, then the individual will carry out the itinerary until everyone else in the simulation has finished, at which point the individual will break out of the loop and terminate.

**Blanket Search.** The last behaviour is specific to the blanket search scenario. When an individual is assigned this command it will search every compartment within the WT zone specified and each room will be searched for a length of time as specified by the range defined in the command (or, if blank, proportional to the area of the WT zone to be searched). The crew member will initially move to its dispersal station which will be the first compartment that they search. Once there, they will wait for the command for the search to start. This will be the point at which all other crew members with a blanket search command have reached their dispersal station. At this point the individual will start searching their assigned WT zone, searching each WT compartment in turn.

	A	B	C	D	E
1	WHO	Action_1	Action_2	Action_3	Action_4
2	ALL	BEGIN			
3	ALL	GOTO_ST_1	CONTINUE		
4	FIREFIGHTERS	DRESS_4_FIRE			
5	54	CHECK_SWIC_#Zone_3#Zone_4#	GOTO_ST_1		
6	52	CHECK_SWIC_#Zone_3#Zone_4#	GOTO_ST_1		
7	112	CHECK_SWIC_#Zone_1#Zone_2#	GOTO_ST_1		
8	49	CHECK_SWIC_#Zone_1#Zone_2#	GOTO_ST_1		
9	ALL	END			
10					

Figure E-3 - Example of the implementation of the new language for “State\_1\_preps”.

	A	B	C	D	E
1	WHO	Action1	Action2	Action3	Action4
2	ALL	BEGIN			
3	CIVILIANS	CIV_NUMBER_60			
4	CIVILIANS	CIV_GROUPS_6			
5	CIVILIANS	CIV_LOWEST_DECK_No_2_deck			
6	ALL	GOTO_EM_ST			
7	CIVILIANS	GOTO_MUST_ST			
8	ALL	END			
9					

Figure E-4 - Example of the implementation of the new language for “IMO\_DAY\_A”.

## **KCL**

The KCL file produced as an output from process A (above) contains all the information described in points 1 to 6, is defined in SURFCON and automatically exported by means of running a macro file in PARAMARINE. The macro file is a standard program, written in PARAMARINE's programming language that allows to automatically produce the KCL file that will be used as the input for the interface software modules.

Future GRC developments of PARAMARINE–SURFCON may see the addition of new output formats and new functionalities which could be more useful for transferring the model to maritimeEXODUS, replicating what the interface software is able to achieve by using existing functions, but perhaps in a more efficient manner.

### **(B) Syntax translation and simulation setup**

This second step is taken care of by the modules of the interface software described below (points 7 to 9). It requires minimal user input and is performed in just under one hour of computational time using a normal desktop computer.

#### **(7) Syntax Translation**

The KCL file is a macro containing instructions to recreate the SURFCON file and all the information relevant to running the personnel movement simulations. The first module of the interface software interprets these instructions and calculates the absolute numerical values (such as locations) and relative links (generating task lists). This operation is automatically performed by a Visual Basic Script running within MS Excel. This resolved version of the KCL is then passed to another module of the software where the information is formatted in order to fit with the maritimeEXODUS input requirements. The translation of the syntax is completely automatic.

#### **(8) Scenario selection**

When step (7) has been completed, the interface software prompts the designer with the option of selecting in which scenarios the design should be assessed. This module of the prototype has been implemented using HTML and JavaScript, and runs in an internet browser window as shown in Figure E-6. The scenarios selected influences the weight factors in the behavioural matrix and changes all the relevant parameters as appropriate.

**Geometry Selection Object**

1) Load the MTA    
 2) Load the DXF

**Scenario Selection Object**

1)        
 2) INITIAL CONDITION  
       

Scenario description

 3) FINAL CONDITION

>>> RUN <<<

Figure E-5 - User interface of the geometry and scenario selection module (before selection).

**Geometry Selection Object**

1) Load the MTA  Design v32.MTA  
 2) Load the DXF  Design v32.DXF

**Scenario Selection Object**

1)        
 2) INITIAL CONDITION  
       

State 1 prep. - step by step / flow chart description  
  
 1) State 1 prep. is called via public address system.  
 2) Everyone goes to their cabin to collect life vest and fire fighting equipment.  
 3) Everyone goes to their Action Station for State 1  
 4) Water tight doors and hatches are closed en route (Z).

 3) FINAL CONDITION

>>> RUN <<<

Figure E-6 - User interface of the geometry and scenario selection module (after selection).

Different design phases and activities will select different scenario sets:-

- Assessing the design in one predefined scenario  
Specialist designs and detail design assessments
- Assessing the design in a number of predefined scenarios  
Comparison of multiple design options
- Defining a custom scenario by selecting its start and final conditions  
Specialist designs and in service assessments
- Selecting a comprehensive package of all predefined scenarios  
Final assessment and refinement of design

The scenario selection module feeds information into another sub-module: the Scenario Generator. This was designed and constructed as a simpler, semi-automatic method of implementing itineraries in maritimeEXODUS. Previously it was necessary for the user to implement all the itineraries by hand and by navigating through a complex interface (in EXODUS). This was an extremely tedious, time consuming and error prone process and so the concept of the Scenario Generator was devised. The candidate designed the Scenario Generator sub-module to enable a rapid specification of complex itineraries and their association to a large number of crew members.

The Scenario Generator extracts all the required information regarding the population and associates it with the data defining the selected scenario. Using this information the Scenario Generator produces an SSF (Scenario Specification File) which contains all the information required by maritimeEXODUS to create the population along with their itineraries in a format which maritimeEXODUS can read in. The scenario scripting language used by the SSF also instructs maritimeEXODUS about how the model should be set up, for instance the status of WT doors (open or closed), the angle of any heel and trim. In addition to extracting the population and their itineraries from the KCL file, the Scenario Generator also includes the capabilities for the user to define the population manually along with their itineraries through its simplified interface. This important module of the interface software has another characteristic that further simplifies the overall integration: the information contained in the SSF file is translated and included in the NMTA file so that only one file needs to be transferred to maritimeEXODUS.

## **(9) Output Selection**

In a similar fashion to step 8, the designer will be prompted with the option of selecting the type of output to be produced by the design assessment. The type of output selected will control what data is stored by maritimeEXODUS during the simulations and will also control the feedback from the simulation.

This functionality has been introduced by the candidate in order to reduce both computational time and output file dimensions. All this information will then be included in a single new file (i.e. the NMTA file) and transferred to maritimeEXODUS for processing.

## NMTA

The file type maritimeEXODUS normally stores and retrieves all the information necessary to set up a specific simulation can be either an EXO or a MTA file. The EXO file is a FSEG compiled proprietary format that can be produced by all programs in the EXODUS suite, while the MTA (MeTadata) file is a scenario file extension specific to maritimeEXODUS. Both files contain the specification of the nature of the scenarios and all information required to run the simulations, including the geometry of the simulated environment.

The MTA, however, is an ASCII file (text based), therefore understandable and usable by third parties and the candidate, in collaboration with the UoG FSEG team, developed a new version of this file to cater for the additional requirements of the integration with PARAMARINE-SURFCON. The size of this new file type was named NMTA, acronym of “New MeTadata” file i.e. an upgraded and simplified maritimeEXODUS scenario file extension.

The new file (NMTA) has been reduced in size by simplifying the structure of the information it contains and by removing the necessity to include information about the geometry of the virtual environment the simulations are based on. The information about the geometry, in fact, is transferred across by means of DXF files, as described in point 1.

The NMTA is an enhanced version of the MTA file, as it also includes all the additional information collected during step A (above) and necessary to run the new type of simulations described in this thesis.

### (C) maritimeEXODUS

Taking the NMTA and the DXF files as input, maritimeEXODUS will perform the simulations (10) and produce output data (11).

### (10) Simulations

In this phase the simulation of the required scenarios will be performed by maritimeEXODUS, based on the information provided with the NMTA and the DXF files. maritimeEXODUS will generate itineraries and perform all the requested simulations according to its core algorithms and using the new functionalities developed by the UoG FSEG team to accommodate the needs of performing the type or personnel movement simulation required by the research presented in this thesis. Due to the stochastic nature of the core module of maritimeEXODUS, the same simulation will be performed a number of times (usually from 50 to 100 times) in order to produce a meaningful statistical distribution of the simulation results. Once the NMTA file is loaded the process would be completely automatic and no user input should be required in this phase. At the end of this process, maritimeEXODUS produces a simulation output database (see point 11).

## (11) Simulation Output

After running all the simulations for the required scenarios, maritimeEXODUS produces a simulation output database. This database contains numerical, graphical and textual information. There is the possibility to run a post-processing module that will use the database to generate two-dimensional animated graphics which allows the user to observe the details of the simulation in the time domain and in a visual format.

In addition, FSEG has also the opportunity to select some of the most relevant simulations (e.g. the best performing one or the one where particular problems occur) and run them into a post-processor virtual-reality graphics environment, known as vrEXODUS, which will generate an animated three-dimensional representation of the selected simulations. This, however, not only is a computationally intensive operation which requires dedicated high-speed computers, but also is an option that produces an output only visible using a dedicated software produced by the UoG FSEG and not commercially available.

In order to avoid the limitations described above and to integrate the results of the simulations back into the design environment, the candidate developed a module of the interface software able to select the output produced by maritimeEXODUS, translate its syntax and render it in an open source tool (i.e. a VRML viewer, see Section 3.9) as well as is PARAMARINE-SURFCON design environment.

Evaluating human factors issues using simulation software such as maritimeEXODUS can be a long and complex process since the analysis requires the identification of relevant evaluation scenarios and the interpretation of a considerable amount of simulation data. Moreover, the complexity of the task grows as the size and complexity of the vessel increases and as the number and type of evaluation scenarios considered increases.

In addition, in order to simplify the process of analysing the simulation results and facilitate the designer in extracting the information relevant to evolving the design, a new output format was developed by UoG in collaboration with the candidate: the human performance matrix (HPMx) as described in Sub-Section 3.6.1. From a naval architectural viewpoint, the candidate developed a procedure that allows both accurate and rapid assessment the design (intended, in this case, as the vessel's layout together with the crew operating procedures).

The systematic and transparent methodology for assessing the performance of the ship design resulted in the FSEG team development of the HPMx [Deere et al., 2007]. The HPMx can be used as a stand-alone discriminating and diagnostic tool, but can also be used by the interface software. The interface software, in fact, can post-process the data and output numerical results of every simulation performed among the relevant average values and include those values a separate database, ready for being analysed (quantitatively in tabular or graphical form) or visualised (for qualitative and quantitative analysis).

### (D) Post processing of the output from maritimeEXODUS.

Integrating the information shown in Figure E-2, Figure E-7 shows more details of how the information is transferred from the maritimeEXODUS simulations back to the PARAMARINE-SURFCON ship definition and the VRML visualisation tool.

The use of two translation tools (the UoG developed “HPMx Producer” and “HPMx Analyser” developed by the candidate as a module of the interface software) allowed a degree of decoupling of the two main tools and allowed each research partner to focus on their specialist domains – personnel movement performance analysis (UoG) and the effective integration of such analyses into the ship design process (UCL).

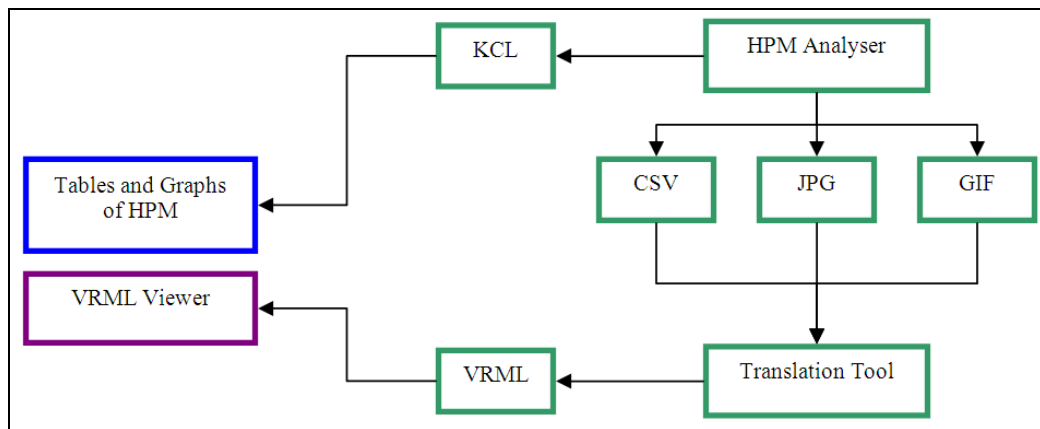


Figure E-7 - Detail of the interface flowchart showing the data transferred from maritimeEXODUS to PARAMARINE-SURFCON and the VRML visualisation tool.

The output from the “HPMx Producer” is the Human Performance Matrix described in Sub-Section 3.6.1 and stored as a CSV file. The “HPMx Analyser” will then translate the CSV into a KCL file which, once loaded in PARAMARINE, allows to generate and display the matrix scores for each design, the individual scenario scores for each design and also the Performance Measure scores. At this stage the naval architect can analyse the results in the form of tables and graphs as described below in step (E).

### (12) Output selection

This module collects the output from maritimeEXODUS and merges them with the information stored by module 7 in an Excel database. The designer would then work through the interface software evaluating the results produced by the simulations. This process will allow the determination of the overall quality of results produced and which ones should be displayed in SURFCON. The data corresponding to the selected options will then be passed on to the next module.



### **(13) Syntax Translation**

This module defines appropriate commands to generate the required visualisations in SURFCON as described in 14 and 15. The information is stored in a KCL file which can be automatically executed by SURFCON.

In addition, this module generates a series of WRL files (one for each scenario selected in 12) and these files can be loaded in a VRML viewer where an alternative visualisation of the results can be used to produce information relevant to the designers to decide upon and accordingly modify the design (point 16).

### **(E) Visualisation and use of the selected output data**

This final step of the process devised by the candidate consists in rendering the output data selected (in point 12) in a usable form, where the designer is able to extract the necessary information about the design and modify the model as appropriate.

### **(14) Numerical output**

The KCL macro file can be used to generate a table within SURFCON showing the Human Performance Matrix using the KCL spreadsheet commands already available in SURFCON. The same KCL produces a summary table with references to the spreadsheet mentioned above, in order to facilitate the designers' navigation of the HPMx and the identification of the most relevant data.

### **(15) Graphs**

The KCL may be also used to generate graphs to represent the variation of key performance metrics in SURFCON. A number of graphs are produced in order to prompt the designer with the correct amount of information to decide upon and accordingly modify the design. These graphs show different information as position-related or time-related occurrence of events. The graph functionality in SURFCON is expected to be enhanced in the next commercial release providing more options for this method of display.

### **(16) Visualisation options**

The candidate conducted additional investigations to examine the possibility of utilising existing SURFCON functionalities to render alternative graphical visualisations of the simulations' output data and information. One of the solutions would have been using the same visualisation used with the Demonstrator (see Sub-Section 3.8.1).

The candidate investigated the possibilities for using existing PARAMARINE-SURFCON functionality to provide interactive 3D representations in the ship design modelling environment. Although this work showed that interactive visualisations were possible in PARAMARINE-SURFCON, the resulting file sizes were unwieldy for use in the fluid early stages of ship design. In addition, the extremely big size of the PARAMARINE files (i.e. ".design") resulting from this

process rendered the program very slow and unstable, therefore un-usable. For these reasons, this option was not developed.

An alternative approach of overlaying 2D images and animations over the 3D model was proposed by the candidate, but this is not currently supported by SURFCON. Subsequent discussions with GRC Ltd. indicated that the time required to make the necessary modifications for this functionality would have gone well beyond the timeframe for completing this research, therefore this option was not pursued within PARAMARINE.

The use of static images (e.g. BMP, PNG and JPEG files) and 2-D animations (e.g. GIF and AVI files) is envisioned in future releases of PARAMARINE. Accepting these file types will necessitate modification to PARAMARINE–SURFCON core model to provide new KCL commands for the generation and utilisation of the appropriate graphical objects. Discussions between UCL and GRC have taken place and the specification for this new functionality; its implementation and its envisaged use have been submitted. As a consequence, GRC have recently announced the introduction of the texture map functionality, as it has a number of applications outside simulation [Forrest, 2008]. If this functionality can be controlled via the KCL macro system, then it will be possible to develop a new module of the interface software, capable of generating this KCL file, thus allowing simulation results to be viewed in the ship design software environment.

### **(17) The VRML viewer**

The candidate investigated and examined the opportunity of using other visualisation means. Investigations have been successfully carried out into the utilisation of non-SURFCON based virtual reality environments for the visualisation of simulation results. One of the most appropriate visualisation techniques appeared to be the one using the Virtual Reality Modelling Language (VRML) and the candidate developed a working example showing how this visualisation can benefit the designer by including all relevant information in a visual, numerical and interactive tool (see Section 3.9). This makes use of a third-party viewer operating within a web browser, and can provide an interactive display with 3D shapes, static texture maps (in JPG format), animated images (in GIF format) and videos (in AVI, WMV or MPEG formats).

Examples of the visualisations developed are shown in Figure E-8 and in Figure 3.9.3 (at page 110). In each of these figures, the footfall density map resulting from a maritimeEXODUS simulation is shown, with vertical bars providing a visual indicator of the maximum time the watertight doors in specific locations were continuously open during the complete scenario. In addition to the static images showing cumulative measurements (e.g. the footfall density map) these visualisation can also show animations of a complete simulation for each scenario. This visualisation tool developed by the candidate is particularly useful in examining the behaviour of the individuals in the simulation and relating this to the resulting numerical measurements. Comparing Figure E-8 and Figure 3.9.3 shows that this view can also be rotated and zoomed.

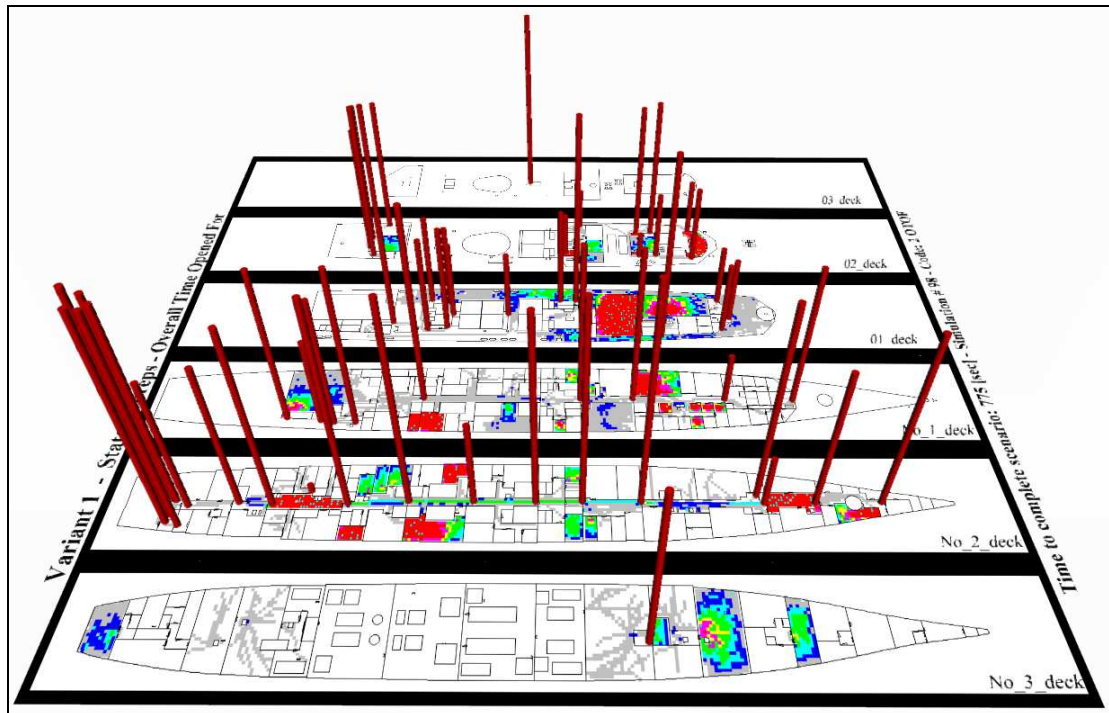


Figure E-8 - Example of the VRML visualisation, showing a representative set of simulation results on the Type 22 Batch III baseline.

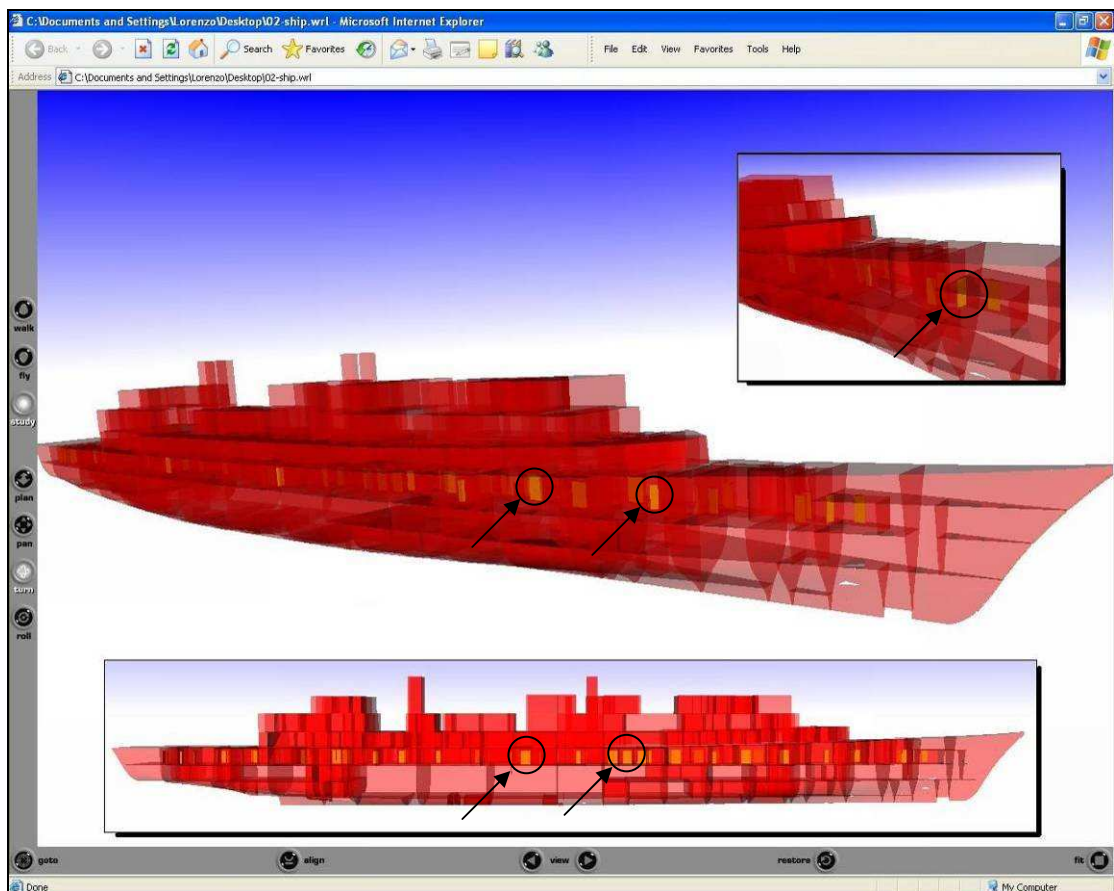


Figure E-9 - Example of different VRML visualisations showing the internal subdivision of the model and all horizontal connectivity items (in yellow- some examples circled) on No 2 Deck.

## Appendix F - List of publications

### Papers Published

- Andrews, D. J., Casarosa, L., Pawling, R., Galea, E., Deere, S., Lawrence, P.,  
“Integrating Personnel Movement Simulation into Preliminary Ship Design”  
International Journal of Maritime Engineering (IJME) Part A1, 2008.  
Discussion and Authors’ reply. IJME, Vol. 150, Part A3, 2008.  
(Included as Appendix G.1).
- Andrews, D. J., Casarosa, L., and Pawling, R., “Interactive Computer Graphics and  
Simulation in Preliminary Ship Design”, COMPIT 2008, Liege, Belgium,  
April 2008.
- Andrews, D. J., Casarosa, L., Pawling, R., Galea, E., Deere, S., Lawrence, P.,  
“Integrating Personnel Movement Simulation into Preliminary Ship Design”,  
Human Factors in Ship Design, Safety & Operation, RINA London, UK March  
2007.
- Andrews, D. J., Casarosa, L. and Pawling, R. “Integrating the Simulation of  
Operations into Preliminary Ship Design.” CETENA NAV06 International  
Conference on Ship and Shipping Research, Genoa - Italy Oct. 2006.
- Andrews, D. J., Casarosa, L., Pawling, R., Galea, E.R., Deere, S., Lawrence, P.,  
Gwynne, S. and Boxall P., “Integrating Ship Design and Personnel Simulation”  
Proc. International Naval Engineering Conference (INEC) 2006, WMTC  
IMarEST, London, March 2006.
- Andrews, D. J., Casarosa, L. and Pawling, R., “Integrating Ergonomics into Ship  
Design.” proc. CETENA Human Factors Conference, La Spezia Italy, Oct 2005.

## **Appendix G - Selected papers and publications**

### **G.1 - Integrating personnel movement simulation into preliminary ship design**

D. Andrews, L. Casarosa and R. Pawling, University College London, UK  
E. Galea, S. Deere and P. Lawrence, University of Greenwich, UK

Published: International Journal of Maritime Engineering (IJME) Vol.150 Part A1, 2008. Discussion and Authors' reply: IJME, Vol. 150, Part A3, 2008.

#### **SUMMARY**

Traditionally, when designing a ship the driving issues are seen to be powering, stability, strength and seakeeping. Issues related to ship operations and evolutions are investigated later in the design process, within the constraint of a fixed layout. This can result in operational inefficiencies and limitations, excessive crew numbers and potentially hazardous situations.

This paper summarises work by University College London and the University of Greenwich prior to the completion of a three year EPSRC funded research project to integrate the simulation of personnel movement into early stage ship design. This integration is intended to facilitate the assessment of onboard operations while the design is still highly amenable to change.

The project brings together the University of Greenwich developed maritimeEXODUS personnel movement simulation software and the SURFCON implementation of the Design Building Block approach to early stage ship design, which originated with the UCL Ship Design Research team and has been implemented within the PARAMARINE ship design system produced by Graphics research Corporation. Central to the success of this project is the definition of a suitable series of Performance Measures (PM) which can be used to assess the human performance of the design in different operational scenarios.

The paper outlines the progress made on deriving the PM from human dynamics criteria measured in simulations and their incorporation into a Human Performance Metric (HPM) for analysis. It describes the production of a series of SURFCON ship designs, based on the Royal Navy's Type 22 Batch 3 frigate, and their analysis using the PARAMARINE and maritimeEXODUS software. Conclusions on the work to date and for the remainder of the project are presented addressing the integration of personnel movement simulation into the preliminary ship design process.

#### **1. INTRODUCTION**

##### **1.1 PERSONNEL MOVEMENT ISSUES IN SHIP DESIGN**

Human Factors (HF) have a significant impact on the design of ships and can be considered at two levels: that of micro-ergonomics and of macro-ergonomics. Micro-ergonomics applies at the detailed level of design, to achieve effective person-machine interfaces and to conduct specific maintenance and repair operations to the ship and its equipment. Historically, macro-ergonomics has been

adopted as systems-based term, encompassing HF related organisational and management aspects of the design, including designing the watch-keeping organisation, assessing the trade off between automation and overall manning [1].

Apart from these two levels of HF application there is the important aspect of addressing personnel movement on board ship as a major influence on the operability and usability of the whole ship. This is strongly related to the overall physical arrangements or architecture of the vessel [2]. In order to assess the aspects related to personnel movement in the ship, the configuration at an early stage of the design process has to be accurately yet flexibly modelled. That is to say the model must provide a broad definition of the main configurational features. Up to the present only after the broad form of the ship's layout has been finalised and the traditional naval architectural issues (e.g. powering, stability, strength and seakeeping) have been addressed, are issues related to crewing, ship operations and evolutions then investigated, and only then within those overall design constraints. It can be seen that this relatively late consideration of personnel movement aspects could then result in significant operational inefficiencies and potentially hazardous environments, in particular on a combatant vessel.

Once the ship design is into the detailed development stage then detailed CAD models can be used by specialist experts to assess the relevant Human Factors aspects, as part of evaluating the usability of a given design. A typical example of micro-ergonomics features appraisal is the use of computer generated models in conjunction with virtual reality and simulation software packages to perform real-time 3-D assessment of the practicality of both the operation and maintenance of onboard systems. An example of this was the simulation using, the simulation tool VSTEP, of the operator position and associated sightlines on a dredger [3].

However, it has been argued in Reference 4 that computer aided graphics now provide the ship designer with the ability to consider the ship configuration in a more interactive manner from the earliest stages of design. Thus a wide range of HF issues related to ship operations can be considered at these early design stages, as they influence the location, layout and sizing of critical spaces, such as the Bridge, Ship Control Centre, Operations Room, machinery spaces, accommodation areas, and the main access routes linking them. In addition to the main ship design stylistic decisions and considerations of gross layout and operational space design one of the important aspects, where HF considerations can have significant design and cost impact, is in achieving a more efficient configuration, thereby reducing the required manning levels. Recent studies by CETENA SpA and the Italian Navy, aimed at reducing costs and optimizing manning, have featured a range of HF and Human-Systems Integration (HSI) issues [5]. Large-scale personnel movement and evacuation has also been investigated for the Royal Navy's Future Aircraft Carrier (CVF) design, given those ships' intended large complement (circa 1200). The second set of authors from the Fire Safety and Engineering Group (FSEG) at the University of Greenwich (UoG) have undertaken simulations of evacuation for that carrier project using their maritimeEXODUS software [6], which is outlined in Section 2.2.

The movement of personnel is one of the key areas of whole-ship usability that can be improved if it is assessed early enough in the design process. Analysis of the

specific issue of personnel and passenger flow in evacuation from passenger vessels is currently covered by IMO MSC Circular 1033 [7] which provides a framework for the conduct of evacuation analysis for the whole ship. However, this only takes into account a single aspect of personnel flow (evacuation) and is undertaken to demonstrate compliance with standards, rather than assessment and improvement of the design at an early stage. Furthermore, it may be inappropriate for naval practice and evacuation procedures since it was defined for civilian passenger evacuation.

## **1.2 THE JOINT UCL/UoG PROJECT**

Current work in the simulation of personnel movement in ships has focused on evacuation, or specific evolutions covering only part of the design. The UCL Design Research Centre (DRC) and UoG Fire Safety Engineering Group (FSEG) are investigating the application of simulation to the personnel movements through out the ship, in a wider variety of operating conditions. This being undertaken as part of a project entitled "Guidance on the Design of Ships for Enhanced Escape and Operation", which is sponsored by the UK Engineering and Physical Sciences Research Council (EPSRC) and UK Ministry of Defence (MoD) Sea Technology Group (STG) (now the Sea Systems Group in the Defence Procurement Agency) [8]. This three year project, which started in October 2004, has five key objectives:-

1. To explore the impact on naval ship configurational design of issues associated with crew manning numbers, function and movement,
2. To identify key performance measures for successful crew performance in normal and extreme conditions,
3. To extend the ship evacuation software maritimeEXODUS to include additional nonemergency simulation capabilities,
4. To extend the ship design software SURFCON so that it can provide a modelling environment that interactively accepts maritimeEXODUS simulation output for a range of crew evolutions,
5. To demonstrate an approach to ship design that integrates ship configuration design with modelling of a range of crewing issues through PARAMARINE-SURFCON.

This work brings together two software packages and centres of knowledge; PARAMARINE-SURFCON, a graphically-centred early stage ship design tool used by the UCL DRC for preliminary ship design; and maritimeEXODUS, an advanced personnel evacuation and movement simulation tool developed by the FSEG at UoG. The project aims to enable the tools to readily interface and for them to be used to generate guidance, not only on design for evacuation but design for enhanced operational effectiveness with regard to personnel issues.

This multidisciplinary research project is intended to demonstrate the advantages of integrating the cutting edge technologies of Personnel Simulation and Ship Configurational Design. In so doing it will enhance the guidance for all parties in the design, regulation, construction and operation of ships with regard to the main aspects related to personnel movement on board.

## 2. RESEARCH TEAMS AND SOFTWARE

### 2.1 THE UCL DESIGN RESEARCH CENTRE AND THE SURFCON DESIGN TOOL

The UCL Design Research Centre (DRC) is a relatively new research organisation sitting alongside the long standing Naval Architecture and Marine Engineering (NAME) Group within the Department of Mechanical Engineering at University College London. Its main area of research is in computer aided preliminary ship design, using the Design Building Block approach and its implementation in the SURFCON tool [4, 9]. The UCL DRC also researches into the wider design environment and innovations, such as simulation based design and concurrent engineering, which are altering the way in which ships can be designed. Like the NAME Group, the DRC has an interest in the design of unconventional and innovative vessels, such as the trimaran, and technologies, such as the all electric ship, but with its own particular focus on the ship architecture typified by the Design Building Block approach and its realisation through the SURFCON tool. Over the last six years a range of design studies, using the DBB approach and the tool have been undertaken, which are summarised in Reference 9.

SURFCON is part of the PARAMARINE software produced by Graphics Research Corporation Limited is an object-based naval architectural design package utilising the commercial ParaSolids modeller as its core [10]. A screenshot of the system in use is shown in Figure 1. The user inserts objects in the "tree pane" on the left of the screen, which shows a logical hierarchal description of the design, whilst any spatial extents or graphical representation are shown in the "graphical pane" on the right of the screen. This provides a constantly updated graphical representation of the current state of the design, a particularly important feature when considering the layout of the vessel. PARAMARINE- SURFCON is not merely a graphical layout tool, it also contains objects for the assessment of the performance of the design across a range of design capabilities, including resistance and propulsion, stability, manoeuvring and radar cross section, in order that each design study is both hydrostatically balanced and achieves the desired levels of performance. A typical numerical analysis is shown in the top right hand box in Figure 1.

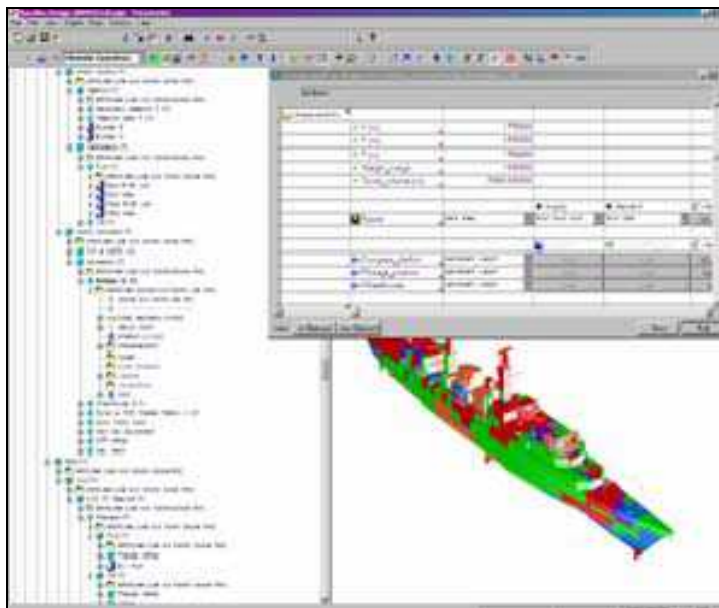


Figure 1: Multiple views of a Design Building Block representation of a frigate using SURFCON.



The fundamental basis of SURFCON and the Design Building Block approach is the Design Building Block object. This is a placeholder or folder in the design space, which contains all descriptive information relevant to a particular function. For example, Figure 2 shows the hierarchical view of a block representing a mess deck for Junior Rates and the corresponding graphical view.

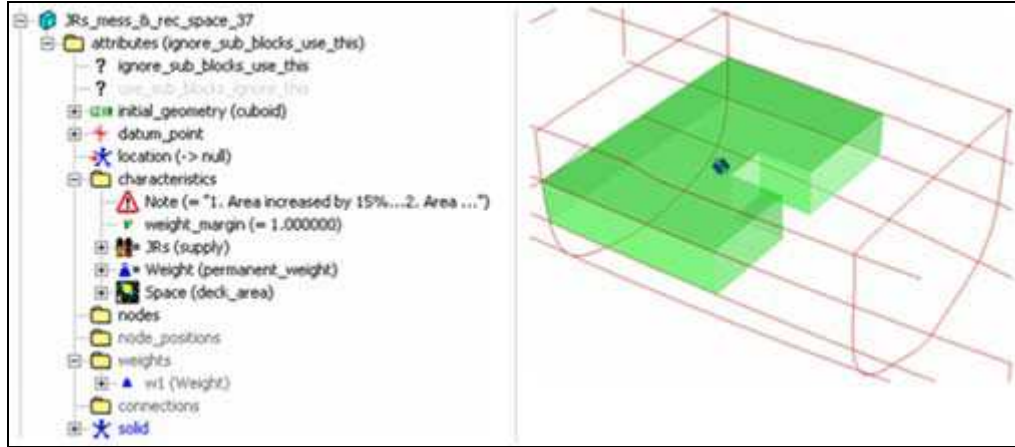


Figure 2: Design Building Block hierarchical and graphical views of a mess deck.

The Design Building Block approach to early stage ship design seeks to encourage a more holistic approach to the development of the ship design solution. Instead of a set of numerical steps or a mechanistic approach, where each aspect of the performance of the design is examined separately and in turn, the integrated nature of the SURFCON implementation in PARMARINE allows aspects of the design's effectiveness to be assessed at the earliest stages of design.

## 2.2 UoG FIRE SAFETY ENGINEERING GROUP AND maritimeEXODUS

The ship evacuation model maritimeEXODUS [6, 11, 12] produced by the Fire Safety Engineering Group (FSEG) of the University of Greenwich was used to perform the personnel simulations presented in this paper. The software has been described in detail in many publications [6, 11, 12] and so only a brief description of the software is presented here. EXODUS is suite of software to simulate the evacuation and circulation of large numbers of people within a variety of complex enclosures. maritimeEXODUS is the ship relevant version of the software. The software takes into consideration people-people, people-fire and people-structure interactions. It comprises five core interacting sub-models: the Passenger, Movement, Behaviour, Toxicity and Hazard sub-models. The software describing these sub-models is rule-based, the progressive motion and behaviour of each individual being determined by a set of heuristics or rules. Many of the rules are stochastic in nature and thus if a simulation is repeated, without any change in its parameters, a slightly different set of results will be generated. It is therefore necessary to run the software a number of times as part of any analysis. These sub-models operate on a region of space defined by the GEOMETRY of the enclosure.

The Geometry can be specified automatically using a DXF file produced by a CAD package or manually using the interactive tools provided. In addition to the representation of the structure itself, the abandonment system can also be explicitly

represented within the model, enabling components of the abandonment system to be modelled individually.

maritimeEXODUS produces a range of output, both graphical and textual. Interactive two-dimensional animated graphics are generated as the software is running which allows the user to observe the evacuation as it takes place. In addition, a post-processor virtual-reality graphics environment, known as vrEXODUS, is provided enabling an animated three-dimensional representation of the evacuation (see Figure 3).

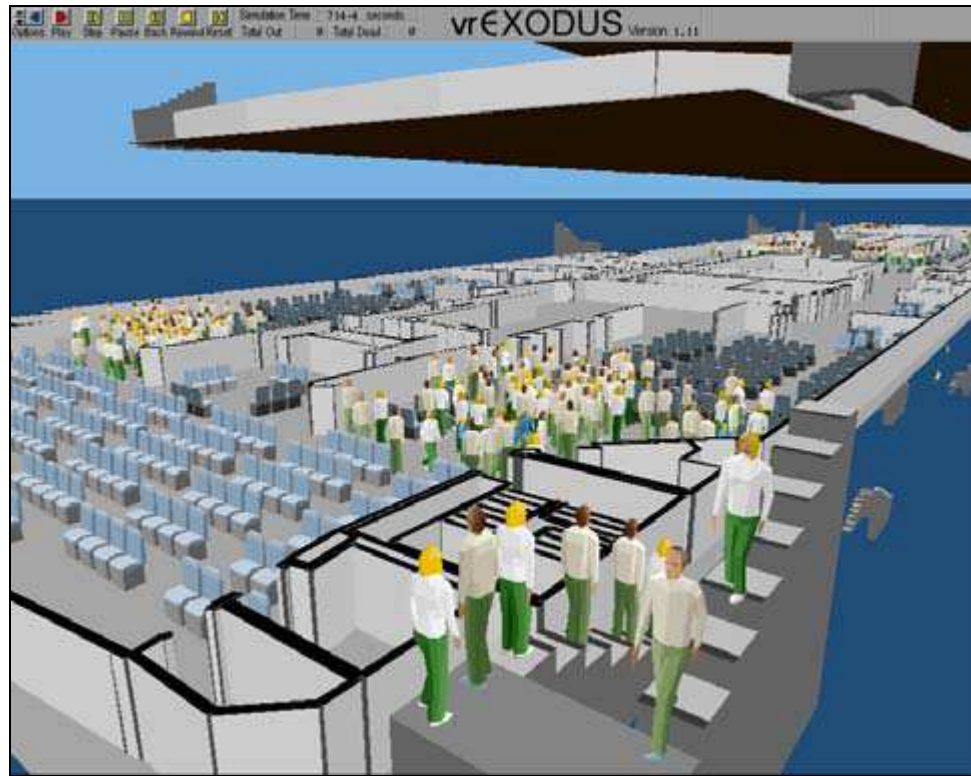


Figure 3: vrEXODUS output showing mustering in a large passenger ship.

The software has a number of unique features such as the ability to incorporate the effects of fire products (e.g. heat, smoke, toxic and irritant gases) on crew and passengers and the ability to include the impact of heel and trim on passenger and crew performance. The software also has the capability to represent the performance of both naval personnel and civilians in the operation of watertight doors, vertical ladders, hatches and 60 degree stairs. Another feature of the software is the ability to assign to passengers and crew a list of tasks to perform. This feature can be used when simulating emergency or normal operations conditions.

As part of the current project, the software's capabilities have been extended through the inclusion of a number of new task capabilities required for normal operations scenarios. Each of these will be briefly described.

'Terminate' command: This feature is used in the normal operations scenarios allowing crew to stay at their last location once a task has been completed. This behaviour allows each individual in the simulation to simply stop once they have completed their assigned tasks. All simulated individuals will remain at their last

location when they have completed their assigned tasks and all simulation parameters (e.g. cumulative wait time) associated with the individual cease to measure performance.

'Repeat' command: This feature is used in the normal operations scenarios allowing crew to repeat a predefined set of tasks a number of times. It was designed for the patrol itinerary used in the particular scenario denoted in the Royal Navy as “State 1 Preps” i.e. crew checking that all compartments are correctly secured following an incident. If the itinerary list of tasks assigned to a crew member contains as the last two tasks, 'terminate' followed by 'repeat', the individual will carry out the entire itinerary until the entire ships compliment have completed the simulation.

'Search compartment' command: This feature instructs crew to enter a particular compartment to undertake a search as part of the blanket search scenario. As the crew member enters the assigned compartment they are assigned a delay time proportional to the floor area of the compartment. The delay time is intended to represent the time required to perform a search of the compartment. Alternatively, the user can specify a minimum and a maximum delay time associated with the search command. If this option is used, the crew member is randomly assigned a search time between the two limits.

'Blanket search' command: This command is specific to the blanket search scenario and instructs specified crew to undertake a detailed search of unoccupied watertight (WT) compartments within a particular WT zone. The user assigns the WT zones to be searched to the appropriate members of the Damage Control and Fire Fighting Party (DCFFP). The software then determines which compartments to search, the order in which they are searched and the location from where the search begins. In the particular blanket search procedure implemented, the search begins from the dispersal station which is the furthest compartment in the assigned WT zone as measured from the Fire Repair Party Post (FRPP) i.e. the starting location of the damage control party. The itinerary assigned to the crew members undertaking the search is made up of multiple 'search compartment' commands. The blanket search operation begins once the relevant crew have all arrived at the dispersal station.

In addition, a separate utility program has been developed, the Human Performance Metric Analyser which automatically constructs the matrix of human performance scores from maritimeEXODUS output that are used in the evaluation of the vessel design.

### 3. HUMAN PERFORMANCE METRICS

In order to gauge the human factors performance of a vessel it is essential to define a range of relevant Evaluation Scenarios (ES) against which the design of the vessel will be tested. These scenarios will effectively define the scope of the challenges that the vessel will be subjected to. In order to gauge vessel performance across a range of criteria, the ES are made up of both evacuation and normal operations scenarios. Relevant evacuation scenarios may include those required by MSC Circular 1033 [4] or their naval equivalent [5]. The normal operations scenarios will very much be dependent on the nature and class of vessel and may include for example time to complete “State 1 Preps”.

As members of the ship's complement may be involved in undertaking different tasks during a particular ES, the ships complement is divided into subgroups. Membership of each subgroup is determined by the nature of the tasks undertaken by the individuals in the particular ES, with each subgroup being made up of personnel undertaking a common set of tasks. These subgroups are labelled Functional Groups (FG). An example of a FG is the 'damage control and fire fighting' group. In practise there may be many FG on board the vessel whose performance must be evaluated e.g. 'Damage control and fire fighting', 'Electronic Warfare', 'Flight', etc.

To evaluate the performance of the FGs in undertaking the tasks required to complete the ES, a range of Performance Measures (PM) are defined. A PM for a naval vessel normal operations scenario may involve the total number of water tight doors (WTD) opened and closed during a particular operation. Some 31 PM have been defined which assess many aspects of crew performance for a surface combatant, such as a frigate. Most PMs are related by a particular theme and so are categorised into groups. Currently, six PM groups have been identified covering the following criteria; Congestion, Environmental, Procedural, Population, Geometric and General. Some of the PMs used in each of these groups are briefly described below.

#### **a) CONGESTION CRITERIA**

This group currently contains two PMs extracted from the IMO Circ. 1033 [7] relating to the level of congestion experienced by FG during an ES. These criteria can be used to identify possible bottlenecks and other causes of congestion. These PM are: C1: 'The number of locations in which the population density exceeds 4 p/m<sup>2</sup> for more than 10% of the overall scenario time' and C2: 'The maximum time that the population density exceeded the regulatory maximum of 4 p/m<sup>2</sup> for 10% of the simulation time'.

#### **b) GENERAL CRITERIA**

This group currently contains five PMs which assess the performance of the FGs in completing general activities associated with the ES. These PMs are; G1: average of the time required by each individual to complete all of their assigned tasks; G2: average of the time spent in transition; G3: time to reach final state; G4: average time spent in congestion and G5: average distance travelled.

#### **c) PROCEDURAL CRITERIA**

This group currently contains three PMs which assess the performance of the FGs in completing specific tasks associated with the ES. These PMs include: P2: 'The average number of operations completed per member of the FG' and P3: 'The average time per task to complete the FGs assigned tasks'.

#### **d) POPULATION CRITERIA**

This group currently contains two PMs which assess factors associated with the number of crew involved in various activities associated with the ES. These PMs are; U1: FG population size and U2: size of the inactive population expressed as a percentage of the number of inactive to the total number of people in the FG.

#### **e) GEOMETRIC CRITERIA**

This group currently contains 14 PMs which assess the performance of the FGs in navigating through various components of the vessel. Individual components of the vessel may be more difficult to traverse than others, for example climbing a ladder

is more time consuming than walking the same distance on a deck. Furthermore, all components which require members of the FG to stop and operate them will incur a time penalty which will slow the performance of the FG and lengthen the time required to complete the ES. These PMs include; M1: the number of WTD used in the ES and M3: the number of times the FG moved between decks.

The suitability of the vessel layout will be evaluated for fitness of purpose through some combination of the PM resulting from the execution of the ES. The list of evaluation scenarios considered in the current implementation of the HPM are, Evacuation Action Stations, Evacuation Normal Day Cruising, Evacuation Normal Night Cruising, State 1 Preps and Blanket Search.

Collectively the particular combination of ES and PM that results in a meaningful measure of the performance of the crew and vessel are described as a Human Performance Metric (HPM). Clearly, the HPM will be specific to the type and class of vessel being investigated. For example, an aircraft carrier will have a different HPM to a submarine. However, the underlying concept of the HPM will be common to all types of vessels and indeed, some of the various components that make up the HPM may even be similar across different types of vessels.

Thus to evaluate the human performance of a particular vessel design X1, a series of PMs are evaluating representing the performance of the FGs in a range of ESs as illustrated in Figure 3. The collection and combination of PMs is known as the HPM. Use of the HPM is intended to aid the ship designer in analysing evacuation/normal operations simulations results quickly and efficiently as well as highlighting any problematic areas within each design. The HPM works by systematically evaluating one layout design against another, whether this is two variants of the same design or two completely different ship designs.

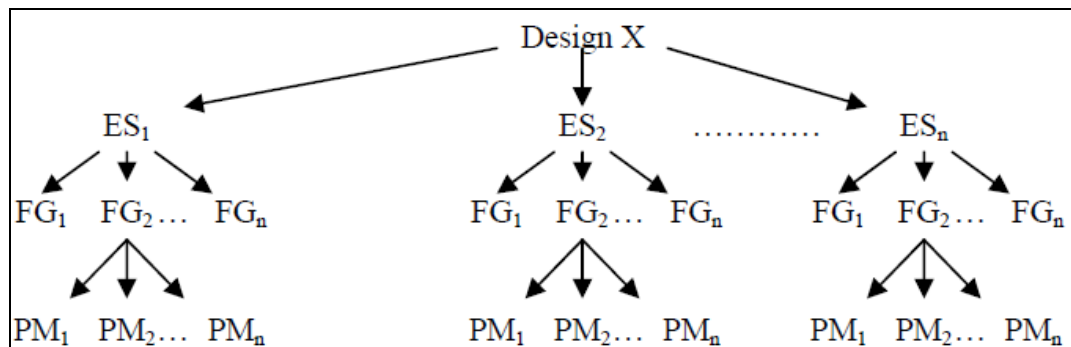


Figure 4: Tree diagram setting out the relationship between the various components of the HPM.

The performance of the vessel in each ES is graded and given a score based on a weighted combination of the PMs. The overall Vessel Performance (VP) is then based on a weighted combination of the scenario scores. The final HPM is depicted in Table 1. The VP for design X can then be compared against the VP for all other designs to determine which design produced the best overall performance on the basis of the weightings. The matrix is also diagnostic in that it allows the identification of which measures contributed to the poor performance of a failed vessel design, or which PM could be improved in a winning design.

Design X	Functional Groups					Scenario Score
Evaluative Scenario	FG <sub>1</sub>	FG <sub>2</sub>	---	FG <sub>n</sub>	--	
ES <sub>1</sub>	a <sub>1</sub>	a <sub>2</sub>	--	a <sub>n</sub>	--	SS <sub>1</sub>
ES <sub>2</sub>	b <sub>1</sub>	b <sub>2</sub>	--	b <sub>n</sub>	--	SS <sub>2</sub>
:	:	:	--	:	--	---
ES <sub>n</sub>	d <sub>1</sub>	d <sub>2</sub>	--	d <sub>n</sub>	--	SS <sub>n</sub>
:	:	:	--	:	--	---
Overall Functional Group Scores	SFG <sub>1</sub>	SFG <sub>2</sub>	---	SFG <sub>n</sub>	---	
Overall design performance						$VP_{DESIGN(X)}$

Table 1: Summarised form of the HPM for design X.

## 4. DEMONSTRATION OF THE INTEGRATION OF SIMULATION AND DESIGN

### 4.1 PROCEDURE

Figure 5 shows the overall procedure for utilising the two software tools for the analysis of personnel movement in early stage design. The upper boxes show the software tools used and the lower boxes show the operations undertaken in each of the tools. The software set consists of PARAMARINE-SURFCON, maritimeEXODUS and interface software tools developed during the joint EPSRC project.

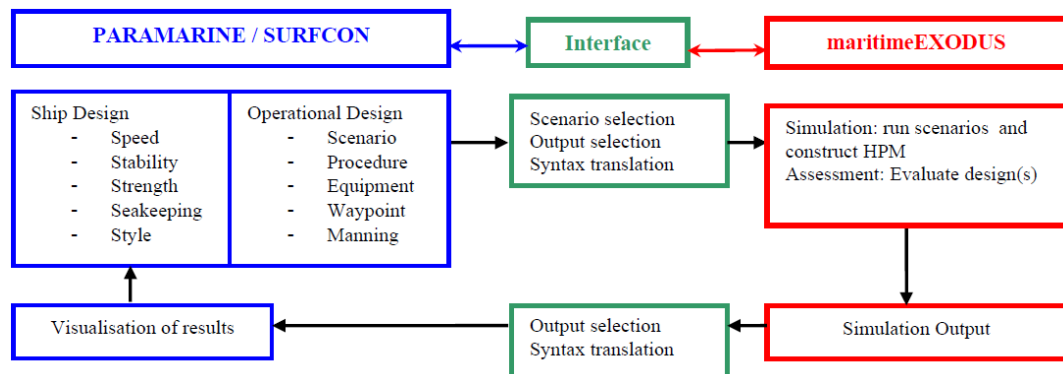


Figure 5: Procedure for personnel movement analysis using separate tools within the joint EPSRC project.

#### 4.1 (a) PARAMARINE-SURFCON

All modelling of the design is undertaken in PARAMARINE-SURFCON, with design features modelled sufficiently to allow the analysis of traditional naval architectural issues. Additional model features are incorporated to allow the investigation of the operations undertaken by the crew. This includes details of the crew's ranks and Functional Groups, and a description of the procedures they are to use in each of the personnel movement scenarios that are to be used to assess the ship design. These features are implemented as a series of tables, formatted to be easily human-readable, and human-comprehensible. These tables are linked to the spatial model of the ship to indicate the main spaces (waypoints) used by each crew member in the scenarios - see Figure 5.

PARAMARINE-SURFCON is also used to visualise the results of maritimeEXODUS simulations in the context of the ship design. In addition to making use of the existing tabular displays of numerical results, the ship design software is used to present graphical representations of both these results and animations of the simulations. The PARAMARINE-SURFCON is being modified by GRC, following specifications developed in the joint EPSRC project, to enhance the graphical display of simulation outputs. This concept of displaying these results, overlaid on the ship design in an interactive manner, places the numerical analyses in context and assists the designer in identifying both the causes of poor performance and possible solutions or improvements for further investigation. It will also contribute to the understanding by designers of the HF related elements of the ship design.

#### **4.1 (b) INTERFACE TOOLS**

The prototype interface toolset consists of a combination of C++ programs, several Excel spreadsheets and macro routines translating and transferring all the information between the two software packages. This is a developmental system, and is not intended to be the final tool, but provides the basic functionality needed to allow SURFCON and maritimeEXODUS to be used together. This implementation of the prototype interface software, and its use, has also allowed a more precise specification of the required functionality to be developed for future tools, thus integrating personnel movement analysis into early stage ship design. This includes issues such as the most efficient way to define the operational procedures to be used by the crew in the simulations and comprehensive and effective post-processing visualisation and representation of the results.

In transferring information from PARAMARINE-SURFCON to maritimeEXODUS the interface tools resolve the many parametric links between Design Building Blocks. The complex design model can be reduced to absolute locations of the geometry (the layout as 2D deck plans), connectivity items, (doors and hatches, ladders and stairs), functional spaces (operations room) and important equipment items (such as gas turbines and liferafts). The instructions describing the scenarios to be simulated are defined in the SURFCON model in tabular form, so that they can be linked to the features of the ship design in the spatial model. This information is transferred to maritimeEXODUS via a "scenario generator" tool, which generates the itineraries (instructions) for each crew member in the simulations requested. Although human interaction is required to run the translation tools, no alteration of the representation of the ship is performed here, thus maintaining the consistency of the models used by the design and analysis tools.

#### **4.1 (c) maritimeEXODUS**

With the layout of the vessel, connections between accessible spaces, simulation scenarios and crew procedures are defined via the Interface tools and maritimeEXODUS is used to perform the simulations. maritimeEXODUS utilises a stochastic model of behaviour, so multiple simulation runs are performed for each of the scenarios. A representative simulation is selected from the multiple runs to populate the HPM. The process of generating the HPM is automatic, a specially developed software tool reading the maritimeEXODUS output and automatically



populating the HPM. The Graphical User Interface of maritimeEXODUS can display the design model being assessed and, within the developmental context of the joint EPSRC project, this is used to check for any errors that may have resulted from the translation process. maritimeEXODUS can also display the results of simulations in tabular and graph form.

It can also record animations of the simulation and produce graphical representations of some personnel movement metrics that have a spatial context. Currently these are viewed by the UoG researchers running the maritimeEXODUS simulations and then sent to the UCL naval architects who alter the ship design. Modifications currently being undertaken will allow maritimeEXODUS to fully exploit the developing PARAMARINE-SURFCON functionalities to display results in the form of tables, graphs and graphics overlaid in the same software environment as the ship design. This will close the loop shown in Figure 5 and allow the naval architects to utilise the results of maritimeEXODUS in a more direct manner, as an input in the early stage design of ships.

## 4.2 VESSELS

The design being investigated in the joint EPSRC project is that of the Type 22 Batch III Frigate. The Type 22 Batch III is an established front line vessel in the Royal Navy and is being used as the base-line ship design (BL-HR). Importantly for the Joint EPSRC project, a complete definition of the required personnel movements during operation evolutions was available for this well established class of vessel (i.e. the Watch and Station Bill).

The SURFCON model of the vessel is at a very high level of definition relative to most early stage ship designs, based as it is on the General Arrangements of the in-service vessel. In addition to the layout of the internal spaces, the model also includes the connectivity items referred to in Section 4.1, such as doors and ladders. The model also includes items of equipment, such as salvage eductors, life rafts and prime movers, that could require crew interaction in some scenarios. Figure 6 shows an area on No. 2 Deck near amidships, with the connectivity items visible. A two dimensional view, generated from the SURFCON model, is also shown.



Figure 6: PARAMARINE-SURFCON 3D model with 2- D drawing showing level of detail for Type 22 Batch III Frigate.



In addition to the spatial model, the Design Building Blocks also contain numerical properties:-

- Permanent weights that scale with ship size;
- Variable weights for ammunition and stores;
- Consumable fluids, supply and demand;
- Electrical power, supply and demand;
- Propulsive power, supply and demand.

This numerical and graphical model represents a balanced design solution and can be modified by the designer. However, the complexity of the model leads to a very high number of connections between the Design Building Blocks and this increases the time and effort required to modify the model. Table 2 compares the level of detail in the Type 22 Batch III model with previous UCL DRC produced SURFCON designs [14, 15]. Figures 7, 8 and 9 show the SURFCON representations of three designs in Table 2 while Tables 3, 4 and 5 summarise each design's principal characteristics.

<b>JOINT EPSRC Type 22 Batch III</b>	
Design Building Blocks	453
Equipment Items	120
Connectivity Items	348
<b>UCL LCS Trimaran [14]</b>	
Design Building Blocks	343
Equipment Items	105
Connectivity Items	0
<b>UCL Dock Mothership [15]</b>	
Design Building Blocks	226
Equipment Items	67
Connectivity Items	0

Table 2: Comparison of detail in PARAMARINE- SURFCON design models.

Table 2 shows that, as well as an increase in the number of entities caused by the addition of connectivity items to the model, the overall level of detail in the baseline is much greater than in those models typically produced in early stage ship design. This increases the risk that the personnel movement analysis will not be performed until too late in the design process. This could then mean significant ship design changes revealed by the analysis will be difficult to incorporate.

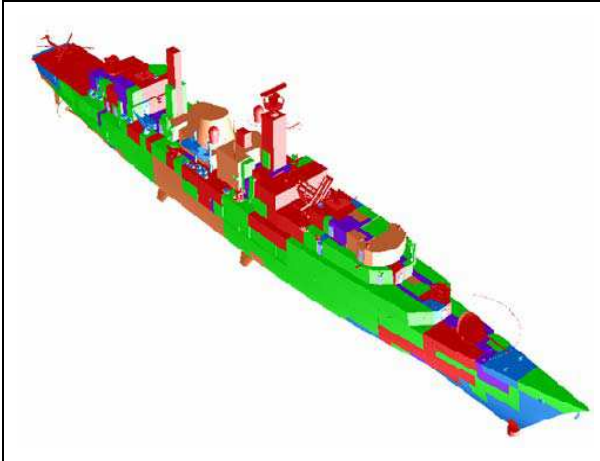


Figure 7: SURFCON Representation of the Type 22 Batch III Frigate.

Deep Displacement, te	5320
Waterline Length, m	136
Overall Length, m	146.5
Max Upperdeck Beam, m	14.75
Max Waterline Beam, m	14.75
Draught, m	4.75
Shaft Power, 18 knots, MW	6
Shaft Power, 30 knots, MW	29

Table 3: Principal Characteristics of Type 22 Batch III used for PARAMARINE-SURFCON Model.

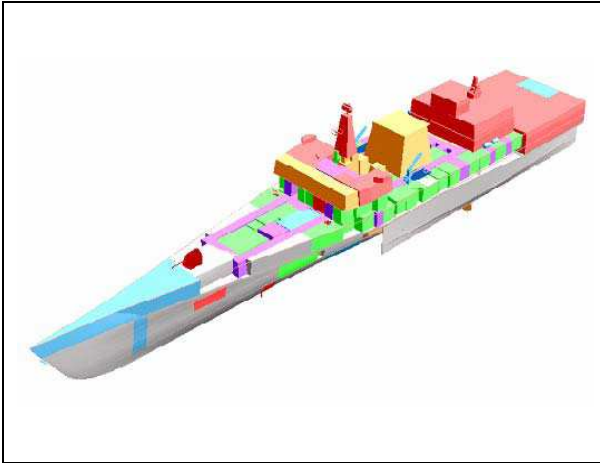


Figure 8: SURFCON Representation of the UCL LCS Trimaran Design Study [14].

Deep Displacement, te	3212
Waterline Length, m	136.3
Overall Length, m	141.3
Max Upperdeck Beam, m	24.5
Max Waterline Beam, m (main hull)	10.5
Draught, m	4.4
Shaft Power, 18 knots, MW	8
Shaft Power, 30 knots, MW	60

Table 4: Principal Characteristics of UCL LCS Trimaran Design Study used for PARAMARINE-SURFCON Model [14].

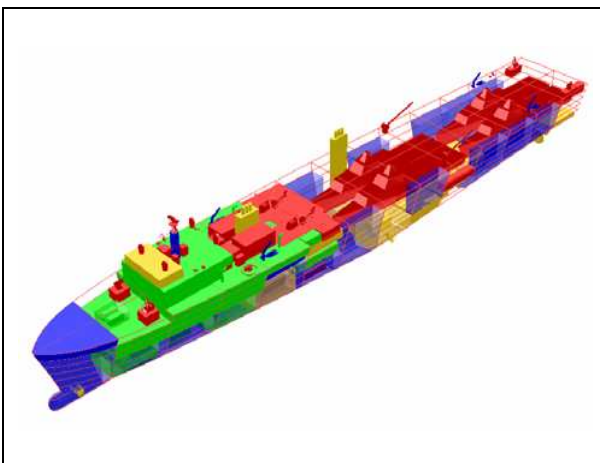


Figure 9: SURFCON Representation of the UCL Dock Variant Mothership Design Study [15].

Deep Displacement, te	32000
Waterline Length, m	250
Overall Length, m	255
Max Upperdeck Beam, m	38
Max Waterline Beam, m	31
Draught, m	7.2
Shaft Power, 18 knots, MW	17
Shaft Power, 30 knots, MW	47

Table 5: Principal Characteristics of UCL Dock Variant Mothership Design Study used for PARAMARINE-SURFCON Model [15].

A single variant of the Type 22 Batch III design has been produced, which features a double passageway on Numbers 1 and 2 Decks (Variant 2), in contrast to the single passageway of the baseline vessel. These two designs are at the same level of detail, but represent two significantly different solutions to internal access, that in Royal Navy ships have traditionally been adopted, respectively, for frigates (single passageway) and destroyers (double passageway) as stylistic choices, rather than decisions based on analysis. The two sets of main access arrangements for Numbers 1 and 2 Decks are compared in Figures 10 and 11. This variant is a balanced design, with numerical and spatial aspects, and so the new design has different overall characteristics - the increased area requirements led to an increase in beam by 2.25m to a maximum of 17m, resulting in a 4.3% increase in displacement and a small decrease in maximum speed.

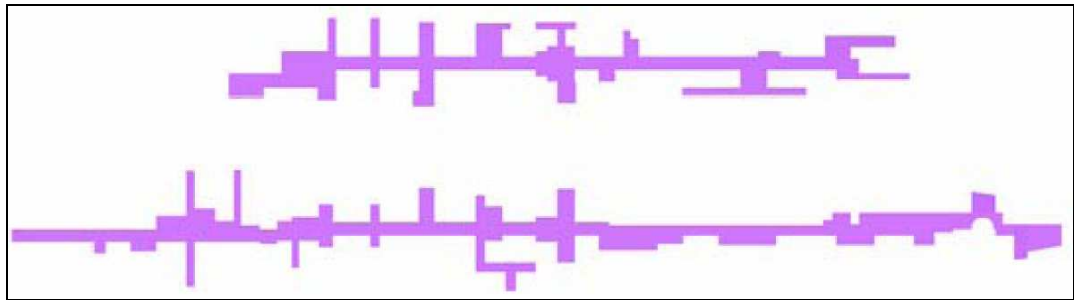


Figure 10: Plan of main passageways on No. 1 & 2 Decks for Type 22 Frigate Variant 1.

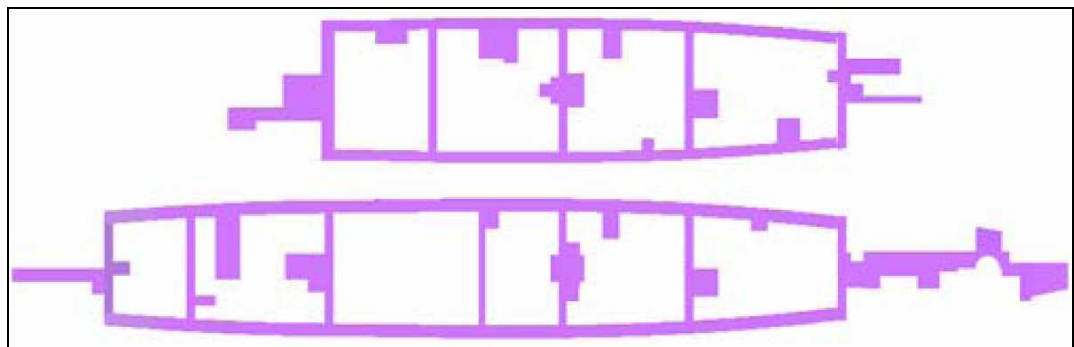


Figure 11: Plan of main passageways on No. 1 & 2 Decks for Type 22 Frigate Variant 2.

### 4.3 ANALYSIS OF HPM OUTCOMES

The use of the HPM concept in evaluating the relative performance of the two design variants is demonstrated in this section. For simplicity, only two evaluation scenarios are considered, one evacuation (Normal Day Cruising: ES1) and one normal operations (State 1 Preps: ES2) scenario. The aim of this analysis is to determine which design variant is the most efficient in terms of its HF performance and whether any improvements to that preferred design can be identified.

The evacuation scenario (ES1) involves the ship's complement moving towards their designated emergency stations ready for the call to abandon ship and so only involves one FG, FG1. For simplicity, the normal operations scenario (ES2) incorporates two FGs, one representing the entire ship's complement FG1 and a

second representing the damage control and fire fighting group FG2. Part of the crew in FG2 move to their appropriate FRPP where they check all the fire fighting equipment and dress in full Fearnought clothing. At the same time, other crew members from FG2 close all the water tight (WT) doors on the vessel in order to bring the vessel to WT integrity Condition Z. For simplicity, both design variants have the same ship's complement and number of crew in FG2. This means that the results produced from the HPM will be a direct result of the change in arrangement between the single passageway (Variant 1) design and the double passageway (Variant 2) design.

In total some 18 Performance Metrics (PMs) are used in the analysis and a set of weights has been defined for each of the PMs and ESs. The weights for the PMs associated with pass/fail evacuation criteria take the greatest values, while the weight for the normal operations ES is 50% greater than the weight for the evacuation scenario.

Providing a greater weight for ES2 emphasises the importance of achieving high HF efficiency in normal operations. In both scenarios, the crew are assumed to take the shortest route to their destination, whether this is an emergency station in the evacuation scenario or a duty station in the normal operations scenario. In reality the crew may take different routes to their target destination however, in order to simplify the analysis, the shortest distance route has been implemented.

As can be seen from the results of the analysis shown in Tables 6 and 7, Variant 1 produces a Vessel Performance (VP) score of 118 while Variant 2 produces a VP score of 132. From this one could conclude that Variant 1 is the more favourable design in terms of its HF performance, according to the measures we have identified, producing an overall vessel performance that is some 12% better than Variant 2. However, the difference between the two design variants is not great and, furthermore, we note that Variant 2 outperformed Variant 1 in the evacuation ES, returning a 5% better performance, while Variant 1 outperformed Variant 2 in the State 1 Preps ES, returning a 22% better performance. The greater emphasis placed on the normal operations scenario (through the larger weight given to this scenario) increases the overall difference between the two designs, strengthening the position of Variant 1 over Variant 2.

Variant 1						
Evaluation scenario	Functional Groups				Scenario Score	Scenario Weight
	FG <sub>1</sub>		FG <sub>2</sub>			
	weight	score	weight	score		
ES <sub>1</sub>	1	45.9	0	0	45.9	1.0
ES <sub>2</sub>	0.5	47.8	0.5	48.8	48.3	1.5
Overall functional group scores	81.7		36.6			
	Overall Vessel HF Performance					118

Table 6: HPM for Variant 1 (single passageway vessel).

Variant 2						
Evaluation scenario	Functional Groups				Scenario Score	Scenario Weight
	FG <sub>1</sub>		FG <sub>2</sub>			
	weight	score	Weight	score		
ES <sub>1</sub>	1	43.8	0	0	43.8	1.0
ES <sub>2</sub>	0.5	62.1	0.5	55.8	59.0	1.5
Overall functional group scores	90.4		41.9			
		Overall Vessel HF Performance				132

Table 7: HPM for Variant 2 (double passageway vessel).

The results from the HPM suggest that Variant 2 is marginally the superior layout for evacuation while Variant 1 returns a significantly better performance in normal operations. This suggests that the overall HF performance of the preferred design (Variant 1) can be enhanced through improving the performance of the vessel in the evacuation scenario.

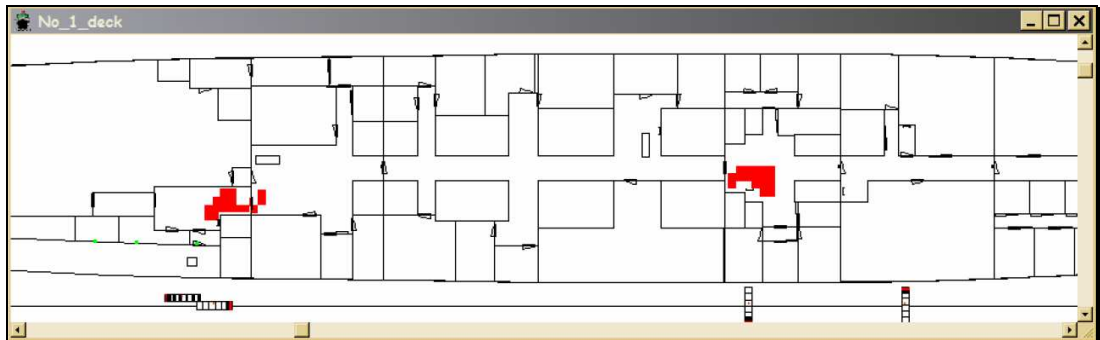


Figure 12: maritimeEXODUS output for Variant 1 showing location of two regions of severe congestion located on No. 1 Deck.

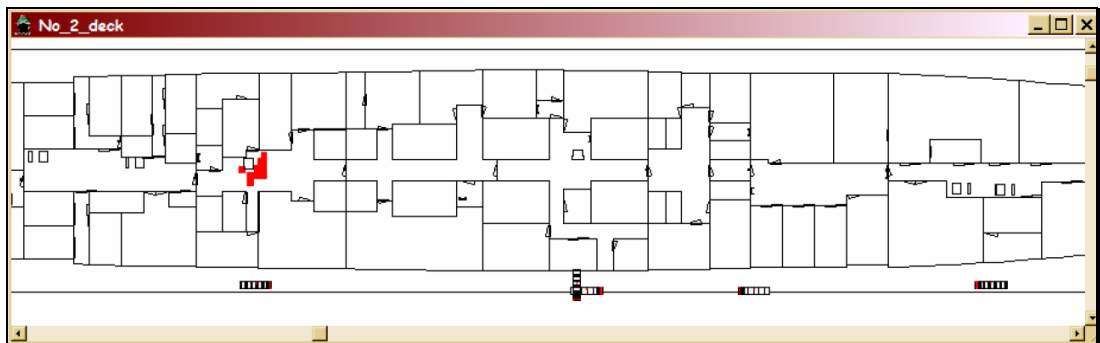


Figure 13: maritimeEXODUS output for Variant 1 showing location of one region of severe congestion located on No. 2 Deck.

A detailed analysis of the Performance Metrics associated with the evacuation ES can suggest areas in which the performance of Variant 1 can be improved. Investigation of the PMs reveals that Variant 1 experienced five areas of severe congestion (three of which are displayed in Figures 12 and 13) compared to only two regions of severe congestion in Variant 2. It is interesting to note that, while both variants comfortably meet the time to muster requirement, they both fail to

meet the congestion standards set in [13] for evacuation and so both variants would be deemed to have failed the evacuation requirements.

Clearly the high levels of congestion apparent in ES 1 for Variant 1 reduce the overall performance of the vessel. To address the severe congestion occurring in Variant 1 requires closer investigation of the vessel's layout. Depicted in Figure 14 is the layout of the vessel together with three of the congestion regions. The rear congestion region on No 01 Deck is caused by the large numbers of crew attempting to use the ladder on No 1 Deck leading to 01 Deck. This congestion creates the second area of congestion occurring on the lower No 2 Deck as crew queue to use the ladder leading up to No 1 Deck. The third area of congestion occurs in the forward part of No 1 deck as large numbers of crew queue to use the ladder leading up to 01 Deck.

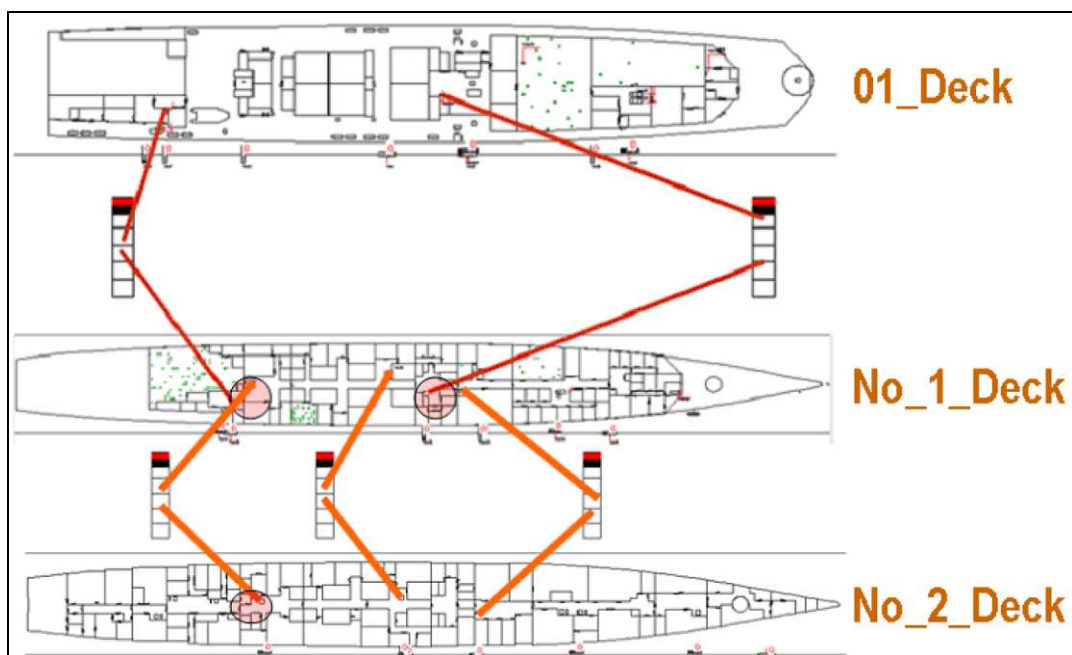


Figure 14: Three decks of Variant 1 indicating location of three large congestion regions (red circles) and associated ladders.

There are a number of possible solutions to these congestion areas. For example, additional ladder capacity up to 01 Deck could be provided at the two congestion regions on No 1 Deck, essentially doubling the capacity of the vertical connections at these two congestion regions. Another possible solution is to provide a third ladder linking No 1 Deck with 01 Deck. This additional ladder could be located mid way between the existing two ladders. Using this approach crew from both congestion regions on No 1 Deck could be drawn to the new ladder, potentially reducing all three congestion regions (see Figure 15). This later suggestion was adopted as Variant 3 and its performance evaluated.



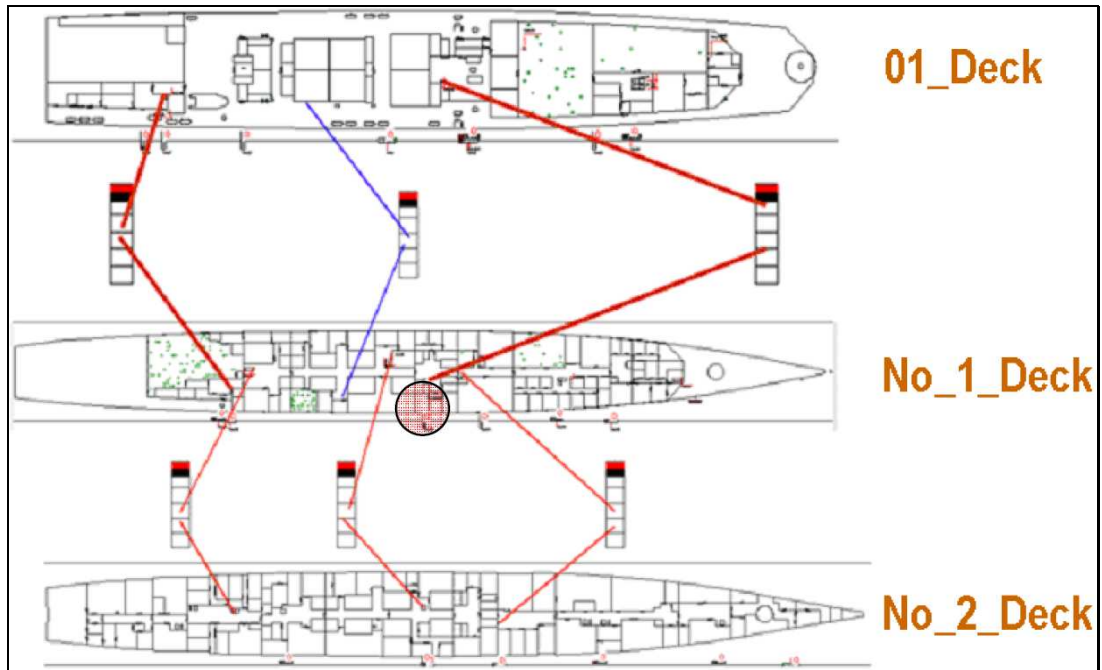


Figure 15: Modified layout of Variant 1 (new Variant 3) with additional ladder connecting No 1 Deck with No 01 Deck.

The proposed modification leads to an overall improvement in vessel performance of some 9.3% with an improvement in the evacuation scenario of some 16.8% and an improvement in the normal operations scenario of some 5% (see Table 8). We also note that Variant 3 now outperforms Variant 2 across the board.

Variant 3						
Evaluation scenario	Functional Groups				Scenario Score	Scenario Weight
	FG <sub>1</sub>		FG <sub>2</sub>			
	weight	score	weight	score		
	ES <sub>1</sub>	1	38.2	0		
ES <sub>2</sub>	0.5	45.2	0.5	46.7	45.9	1.5
Overall functional group scores	72.1		35.0			
	Overall Vessel HF Performance					107

Table 8: HPM for Variant 3 (single passageway vessel with additional ladder).

A closer examination of the relevant PMs reveals that Variant 3 experienced three areas of severe congestion, a reduction from the five areas experienced in Variant 1. Two of the three targeted areas of congestion have been completely removed, while the third area (forward area on No 1 Deck, see Figure 15) is greatly reduced. Thus while the overall performance of Variant 3 is greatly improved, it still fails to meet the congestion standards set in [13] for evacuation. It is also worth noting that a number of the PMs associated with Variant 3 have improved through the addition of the single ladder, these include (see Section 3 (b) and Section 3 (e)): G1 (average time required by each individual to complete all of their assigned tasks) 21% improvement; G4 (average time spent in congestion) 45% improvement; M2 (number of hatches used in the scenario) 11% improvement; M5 (number of

doors used in scenario) 22% improvement; and M14 (most times a WT door was operated) 17% improvement.

A similar detailed analysis to that undertaken for the evacuation scenario could be undertaken for the normal operations scenario which may suggest either procedural or structural changes to Variant 1, improving the performance of the vessel still further. While a detailed analysis is beyond the scope of the current paper, preliminary investigations suggests that, in contrast to the conclusion of the evacuation analysis, the average level of congestion experienced by each crew member is much greater in Variant 2. This detrimentally impacts the performance of the crew. Furthermore, it is important to note that the starting and end locations of crew movements and the number of crew in the various starting locations are quite different for these two ESs.

## **5. FURTHER WORK**

### **5.1 LOWER RESOLUTION MODELS**

To overcome the difficulties found in modifying the high-resolution models of the baseline Type 22 Batch III Frigate and the double-passageway variant, a series of low-resolution models are being developed. These will more closely represent the level of detail usually available in the early stages of ship design. The lower resolution models will represent four more variants:-

- Baseline Type 22 Batch III;
- Double passageway variant;
- Variant with all cabin accommodation to modern standards (groups of cabins represented by single Building Blocks);
- Medium-resolution cabin based accommodation variant (individual cabins each represented by Building Blocks).

The first two designs will allow a comparison of maritimeEXODUS simulation results from high and low resolution versions of the same design. This is a vital issue if any personnel movement analysis is to be integrated into early stage design. There is a trade off between how much detail is needed in the design, for effective simulation of operations, and the need to retain flexibility for early stage design. A related issue is to investigate how much input is required from the designer to define all aspects of the simulation; certain inputs, such as the Watch and Station Bill, could be generated from a library of options, rather than requiring designer input to commence analyses and thus slowing general design progress.

### **5.2 HPM**

The ES used to define the HPM will be extended to include several more evacuation and normal operations scenarios. These will include a selection of the evacuation scenarios identified in [13] and the Blanket Search and Family Day normal operations scenarios.



### **5.3 SENSITIVITY ANALYSIS**

For a given set of ESs, the conclusions drawn from an analysis of the HPM will be dependent on the user defined weights. An inappropriate setting of the weights may amplify unimportant performance differences between variants and mask important differences. Thus in setting the weights it is essential there is a clear understanding of the priorities in evaluating the designs. To develop a better understanding of the impact the weights may have on an evaluation, a weight sensitivity analysis is currently underway.

### **5.4 GUIDANCE**

As indicated by the project's title, "Guidance on the Design of Ships for Enhanced Escape and Operation", the main purpose of the project is to provide guidance on this issue. This will cover several areas:

#### **5.4 (a) THE DESIGN OF SHIPS**

This project aims to provide ship design guidance that can be directly used by the MoD. This will be achieved through the assessment of alternative access and accommodation arrangements. In addition, the project is seeking to identify any features or procedures that could be adopted as "good practice" in design for evacuation and personnel movement related operations.

#### **5.4 (b) THE LEVEL OF DESIGN DETAIL**

This new capability of simulating, as part of the design, the movement of personnel from the early stages of ship design will affect the manner in which design is undertaken. The development of the design procedure is highly coupled to the development of the software tools and this project aims to provide guidance on the best approaches to be adopted. These will ensure effective assessment of personnel movement issues at an early stage. This includes issues such as the level of detail required in the model and the performance measures, that are most useful, to record effective ways of using them in an interactive design environment. Another issue is how best to iterate the design to a solution. The two approaches currently under consideration are to take a single design and modify it to improve the performance, or to produce a range of designs with different styles and then assess them all in comparison. This would be done against both traditional ship design criteria and the newly-available personnel movement performance criteria. These distinct strategies will be compared and their advantages and disadvantages investigated.

#### **5.4 (c) THE WIDER DESIGN PROCESS**

Another issue to be addressed is how to integrate, into the overall design process, the assessment of personnel movement in operational scenarios. The procedures used could be fixed and defined by naval operating procedures, or could be treated as another aspect of the design that could be improved as part of the general design development in a given design. In the latter case, the performance of the personnel could become another aspect of the design to be included in cost-benefit and cost-performance analyses. If such aspects are considered then the main outcome for

the integration of personnel movement and ship architecture will be to facilitate the exchange of information between the ship designer and experts in manning/personnel operational procedures. This would result in their different needs being incorporated in a single decision making process and facilitate a joint working environment, where the ship's material design is evolved alongside the "design of the crew's capabilities".

## 6. CONCLUSIONS

Human Factors influence ship design at many levels. Most HF work relevant to ship design has concentrated on "micro-ergonomics", that is the design of the person-machine interface. Less work has been conducted in the area of whole-ship ergonomics, encompassing issues such as overall configurational layout, personnel movement during operations and operator sightlines and visibility. However, the development of modern computer graphics and of modelling and simulation tools is changing this situation.

This three year project by UCL and UoG is developing tools and approaches for integrating the assessment of personnel movement into the early stages of ship design.

As part of this work, a method, known as the HPM, has been developed to assess the HF performance of naval vessels. This method is intended to be used as a comparative tool, where the performance of one variant is compared with the performance of an alternative variant. However, if appropriate standards are defined, the approach could also be used to evaluate absolute vessel performance. The approach is capable of discriminating between competing designs by selecting the design with the best HF performance, across a range of relevant scenarios. The approach is also diagnostic, providing a means to identify aspects in crew/vessel performance which can be improved. Furthermore, the technique is both systematic and transparent, allowing user priorities to be clearly stated as part of the approach. User priorities can be identified through the selection of the evaluation scenarios to be investigated and the weights assigned to the various components of the HPM.

In addition to the technical issues of modelling and software modification, there is the more general consideration of procedural integration. This project represents the start of bringing whole-ship ergonomics and HF to the fore in ship concept design, such that major design choices can be informed by what has historically been an under-represented issue. This is just one significant area where preliminary ship design can be made more responsive to the aspects of importance not just to owners, but also operators and users.

The two universities and their MoD partner have already explored metrics for the Type 22 frigate and evaluated the issues surrounding the interfacing of the two software packages. The latter task shows that there is a wide range of possible metrics, evolutions and modelling issues appropriate to this interfacing.

While this project addresses the design of naval vessels, the principle behind the proposed approach and the ability of the tools to interface in a seamless manner, has direct applicability, particularly, to the design of commercial passenger vessels.

For ships the overall layout or General Arrangement is the primary mechanism for taking into account the view of the specialist users and of subsystem and equipment designers, while maintaining overall design cohesion. The final output from this project will consist of an integrated tool set, enabling the ship designer to explore the interaction of personnel movement with the ship design, in a range of scenarios. A set of case studies using the tool set will be the primary output, which will provide the basis for guidance to industry and benchmarks for the MoD in the assessment of proposals. This is seen as a means to save considerable time and money in the ship design phases but also in the vessel's through life costs, which can be several times its procurement cost. The project is expected to reinforce the view that, if personnel related considerations are left too late in the design procedure, this could impact significantly on the costs of ownership. It is therefore considered important to introduce consideration of these aspects into the formative stages of the design, in order that trade off studies can comprehend personnel related through life cost implications.

It follows that a more comprehensive design description is required in the preliminary stages, facilitated by the Design Building Block approach. This emphasis on the Human Factors aspects is consistent with the fact that the largest element of the through life cost of a naval combatant is usually directly attributable to the cost of the personnel required to operate the ship and its systems. Design for maintenance is related to efficient personnel movement and the Design Building Block based design description, in conjunction with personnel flow analysis can highlight conflicts early in design. The approach proposed of a Design Building Block based synthesis, in conjunction with the simulation of personnel movement, provides the appropriate front end to a comprehensive design approach for such complex systems. So from investigations, emergent guidance on configurations, which is appropriate to efficient personnel movement, can be provided in a manner that will not conflict with the wider procurement needs. This will lead to clearer requirements, fostering a better basis for competitive responses from industry.

In conclusion, the outcomes from this project are expected to indicate where design can be improved. This should have a direct impact on the through life costs of the vessel, provide a major saving for ship operators, improve the efficiency of the ship design process, reduce design and build time and costs and ensure that the vessel is safer and more efficient for the personnel on board.

## **7. ACKNOWLEDGEMENTS**

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**DISCUSSION** (Vol. 150 Part A1 2008)

## **COMMENT**

**Prof. P. Wrobel**, University College London, UK

This paper is a very welcome development in what has been a somewhat neglected but extremely important facet of ship design. The tighter integration of the EXODUS model within the design process will facilitate the more timely analysis of the all of the issues associated with the movement of personnel - in both normal operation and emergency scenarios – resulting in designs that are both more operable and safer.

A key enabler to this process is the ability to commence the analysis early when the design is more fluid. There is a role for more detailed analysis later in the process to address specific design features, however if this is the only time personnel movement is addressed with analytical rigour then the opportunity is lost and leads to a ship design that is inevitably somewhat compromised.

Another emerging opportunity is to study the major midlife modernisation of ships as new capabilities are introduced, new technologies mature or increased safety standards are required. In the latter category I include the emerging concern about the electro-magnetic hazards associated with the introduction of very high voltage power electrics, high power radars etc.

We used EXODUS in the initial design of the CVF but without the benefit of its integration with a Ship Design Tool. This was cumbersome but valuable. However it raises a question about timeliness versus analytical integrity. EXODUS sets out to undertake a rigorous analysis of personnel movement under a range of conditions. As such it requires a level of design definition that is not available at the formative stage when the ship design is at its most fluid and hence the use of EXODUS is able to make the biggest impact. A simpler tool would suffer the risk of being superficial, however the traditional approach has been to defer its use until the design has matured sufficiently – leading to the lost opportunity mentioned above.

How do the authors envisage allowing designers to have it both ways i.e. the integrity of EXODUS is maintained whilst it is possible to use it at several iterations of the design process, starting early when the design is fluid but the inputs required are immature?

**Prof. H. Hopman**, Delft University of Technology, The Netherlands

The paper presents a new and interesting approach to tackle Human Factors in the early stages of ship design. To me, however, the demonstration of the integration of PARAMARIN-SURFCON and maritime EXODUS on 3 variants of a Type 22 Batch III layout shows some valuable and, sometimes, unexpected results. The paper discusses the differences between Performance Metrics of variants 1 and 2. However, it is not made clear in this paper why under “normal operations” the single passageway design (variant 1) has a better performance than the double passageway design (variant 2). A possible explanation could be that the normal operations scenario as used for the demonstration also involves closing of all watertight doors. As variant 2 has more WT doors, this could have been the reason for variant 2 taking more time in order to bring the vessel to WT integrity Condition Z.

In the paper it is stated by the authors that the level of detail, used for the demonstration, is rather high compared to the level of detail of SURFCON representations used for other design studies. My comment on this is that this is not something to worry about. It is more likely that in near future analysis tools, based on so called “first principles”, will be used more often in early stage of the design. The main reason for this is the ongoing development in computational capacity and speed of computers. Also the need for better, more creative and innovative solutions will lead to the use of “first principles” tools in early stages of the design process. Therefore, it is likely that more effort should be put into the development of new modelling techniques to speed up the level of detail required for these types of calculations rather than trying to reduce the resolution of the simulation tools in early design stage.

Alternatively, for this particular design aspect it probably would have been sufficient to use global design rules for sizing access routes in early design. From the demonstration it can be concluded that the proposed design changes are relatively small and do not really affect the topology and main dimensions of the design. Therefore, you could argue that the use of personnel movement simulation during later stages in the design would be more appropriate and effective.

An important aspect of naval ship design is that the design process should not only concern the design of systems (of systems) but also the design of the management organization needed to operate these systems. In fact, the development of the required management organization should be developed at least in parallel or, more likely, slightly ahead of the development of the systems of the ship.

As stated in the paper, the design of the required management organization, including aspects related to Human Factors, has historically been an underrepresented issue in ship concept design. However, to be able to make preliminary ship design more responsive to these aspects requires not only a high resolution model of the ship but also a high resolution model of the required management organization needed to operate the ship. Therefore, I suggest to the authors that in case of future work more emphasis should be put on the development of new tools to model new and innovative management organizations, flexible and modelled to the same resolution level as used for the ship design

model. It would be interesting to see if a similar approach as the Design Building Block approach can also be used for defining the management organization in the early stages of the project.

**Prof. I. L. Buxton** (Fellow), UK

The authors outline a promising design tool for the naval architect, one which considers design and operation explicitly. Normally these are implicit, e.g. evolution of a design concept through a series of Marks. But with lower procurement numbers and lengthy procurement programmes, that is not a valid approach today for combatant ships. Such ships have much more complex range of scenarios than merchant ships, while there is the perennial problem for the warship designer of whether to optimise for wartime operations, or for peacetime, which might well make up nearly 100% of its life cycle.

The use of such a tool requires a greater familiarity by the naval architect with shipboard operations and associated seagoing experience. The tool could also demonstrate whether adoption of some merchant ship access standards in critical locations might be beneficial, e.g. wider stairways of shallower slope, compared with the traditional ladder and narrow hatch.

**Mr S. Rusling**, UK Ministry of Defence

This is an interesting paper which describes a new approach to addressing issues related to ship layout earlier in the design process than has traditionally been the case. The Human Performance Metric (HPM) is at the heart of the approach and is evaluated by weighting the performance of a number of Functional Groups (FG) under separately weighted Evaluation Scenarios (ES) to give a single measure of Vessel Performance (VP). Whilst welcoming the thrust of the research, it is the utility of the concepts of weightings and a VP that I would question.

It is not clear what the benefit is of having weightings. Whilst setting weightings objectively and independently of a particular layout is a good mechanism for the designer to be clear about his priorities, ship design is primarily an exercise in compromise not of optimisation. In practice, if a particular FG in a specific ES is not performing well, then it will still be necessary for the designer to decide whether he needs to address that aspect of the layout or not, irrespective of the weighting he has applied to it, in the light of other demands on the design.

For a realistic assessment of a specific layout following the approach proposed in the paper, a wide range of FG and ES will need to be addressed and weightings allocated appropriately. There will, however, inevitably be a need to address the underlying performance of the different FG in each of the ES to ascertain what the design drivers are, from a layout perspective, in order to ascertain what corrective action needs to be put in place. Indeed, even with just two FG, two ES and appropriate weightings, the authors found themselves doing this with the results presented in Tables 6 and 7.

Finally, the authors note the need to undertake sensitivity analyses, by changing the user defined weightings, in order to have a better understanding of the impact the

weights have on an evaluation. It is difficult to see how the repetitive calculation of the VP for each combination of weightings adds much value to the evaluation of the layout, other than by assigning a single figure of merit, thereby permitting a ranking to be undertaken for different assumed weightings. Calculating the VP is a mechanistic process and comparing candidate layouts on the basis of this single figure of merit puts too much emphasis on the utility of the VP. It also begs the question “What is an acceptable number for VP?” What is actually important is the underlying acceptability of the proposed layout from a number of discrete viewpoints, not a number purporting to comprehensively evaluate these.

#### AUTHOR’S RESPONSE

The authors would like to thank the four eminent commentators for their comments. We hope our responses to each in turn will clarify further the issues raised in the paper.

In reply to Professor **Wrobel** we would confirm that the University of Greenwich, as developers of the maritimeEXODUS software, undertook much of the early egress analysis for the CVF. We agree that had the integration of maritimeEXODUS with the PARAMARINE-SURFCON ship design tool been available at that time, it would have saved a considerable amount of effort. In addition, had the Human Performance Metric approach described in the paper been available, this too would have saved a considerable amount of time in interpreting the results of the egress scenarios and assessing the overall Human Factors (HF) performance of the vessel. We believe that the capabilities that are now in place will make this type of analysis considerable more time efficient.

Concerning the application of the technique to the analysis of early stage designs, in Section 5.1 of the paper we indicated that analysis of low-resolution designs was underway. The Low Resolution design shown is intended to represent the layout of the vessel in the very early stages of ship design, when much of the interior detail does not exist. It should be noted that adding or removing detail to the vessel design may significantly change the indication of the overall HF performance of the vessel and may mask features of HF performance revealed in the final in service design. Thus the HF performance derived for a Low Resolution design may not model the HF performance of the high-resolution version of the same overall design.

We have now completed analysis of Low, Intermediate and High Resolution designs of the two variants and the analysis suggests that the same conclusions concerning overall vessel HF performance. Thus we suggest that in the early stages of the ship design process, the HPM technique will be useful in determining whether design iterations have improved or degraded HF performance. However, given that in the very early stages of design much of the infrastructure, which will impact HF performance, is not present, it may not be efficient to invest considerable effort in attempts to optimise HF performance. Rather it would be better to use the approach to identify very clear HF problems and to explore radical configurations. The latter will provide indications, in comparison with conventional layouts, as to whether such radical options lead to specific HF advantages.

It is further suggested that the set of evaluation scenarios and performance measures presented in the paper to evaluate the high resolution design variants may not be the most appropriate to evaluate low-resolution variants. The evaluation scenarios



used in the analysis of high resolution designs may need to be simplified, maintaining their essential features but reflecting the lower resolution of the designs. Identifying and testing a set of evaluation scenarios and performance measures appropriate for low-resolution designs should be the subject of further research, ideally undertaken in collaboration with potential end users. The authors suggest the integrity of maritimeEXODUS can be used in the earliest stages of ship design, by using the broad initial design description (equivalent to the stripped down Low Resolution case of the Batch III Type 22) and some generically derived features necessary to enable maritimeEXODUS to simulate personnel movement (e.g. WT doors, vertical accesses). This has now been done.

Professor **Hopman** seeks clarification on the performance difference between the single and dual passageway variants, which we also found somewhat surprising. We did not go into too much detail in the paper to explain all the differences, primarily because the paper was intended to be a demonstration of the method, rather than a detailed exploration of the specific vessel features. However, he is quite correct in concluding that the number of WT doors present in the two design variants is a major factor contributing to the observed HF performance differences in the normal operations scenarios; however it is not the only noteworthy factor in the difference observed.

The average distance travelled by the crew is another significant factor. During the blanket search scenario, the crew members on the single passageway variant need only travel along one central corridor, however for the double passageway variant the crew need to traverse two passageways plus up to seven interconnecting corridors. This extra distance takes time to traverse and contributes to the negative result.

In addition to these differences, it should be noted that both variant designs had a similar number of vertical access routes. However if the double passageway variant was to make best use of its layout then additional vertical access routes should be provided enabling vertical travel points on each main passageway. This may well have compensated for some of the additional travel distance incurred by the crew) as well as possibly reducing the level of congestion incurred. If the double passageway variant was to have additional vertical access routes then perhaps this design variant could have outperformed the single passageway variant. This is felt to be a good example of a critical early design issue, which prior to this research would not have been readily addressable in initial ship design.

It should be noted that the HPM approach outlined in the paper can also be used to investigate the impact of changes in operating procedures for a given design. For example, for a given design, the technique could be used to investigate the impact of reduced crew or a suggested modification to a given scenario.

Professor Hopman's third paragraph implies that the double passageway change does not alter the topology and main dimensions of the design, however, as stated in the text above Figure 10, the vessel's beam increased by 2.25m and consequently, without changing the propulsion fit, the maximum speed marginally reduced. In an actual new design such an access change might be shown to reduce the number of personnel onboard and if this was fed through, then the design sizing

could lead to significant changes in the ship size and cost. This is precisely the motivation behind the investigation.

This leads on to Professor Hopman's comment that with the increasing capability to use "first principles" there may not be the need to strive to enable simulation to be undertaken with the reduced layout resolution we have investigated. This may come to fruition, however if one believes the issue in preliminary design is that of "Requirements Elucidation" (Ref. 16), then as wide and broad an exploration of options early in the process is essential. Pursuing all the possible "first principle" analyses just because that has become possible would be counter to this focus on elucidating the requirement. So one might argue why look at personnel movement so early? We maintain that crew, both in its demands on ship services and impact on configurational drivers, strongly influences initial cost and, furthermore, crew cost dominate naval ship through life costs, hence justifying early integration of personnel movement investigations into preliminary ship design.

Finally, Professor Hopman poses an interesting question with regard to modelling the management organisation for ship operation. Only a few example personnel evolutions, selected by our industrial (UK Ministry of Defence) partner, were addressed in the research, however it would be appropriate to explore many other which should reveal improvements to various onboard operations. With a graphical representation and the simulation outputs, it is suggested the naval manning authorities could become much more directly involved with the ship design evolution and that one might envisage the crew organisation and skill set being "designed" in an interactive manner alongside the ship design.

Professor **Buxton** suggests the use of such an approach as we demonstrate requires a greater familiarity by the naval architect with shipboard operations and hence acquisition of the associated seagoing experience. While we would agree this is desirable, it is not considered essential for the technique. It is suggested that, for the most part, the evaluation scenarios and performance measures will be standardised for a particular type and class of vessel. This will ease the burden on the naval architect to become familiar with operations for a particular ship. However, it is the case that naval ship designers have traditionally been more familiar with ship operations than their commercial equivalents. In the case of UK naval constructors, this was achieved through six months sea time, whereas most other navies converted seagoing marine engineers into the equivalent of the constructor. With the end of the UK arrangement and reliance of the UK MoD on contractors for ship design, the need to give future ship designers such knowledge has been recognised by the UK naval ship design community and thus we hope by bringing HF issues more to the fore in ship design we have helped to reinforce this intent.

We agree that the technique could be used to assess the likely benefit to be derived from introducing standards from merchant and passenger ships into naval vessel design. Indeed, the technique also has application in assessing the Human Factors performance of merchant ships and specifically passenger ships. For example, for passenger ships, the overall design could be assessed not only for the mandatory IMO evacuation performance, but also for boarding and disembarkation performance, the efficiency in which dinning rooms could be filled/emptied,

the optimal location of retail and casino locations, etc. All of these factors could be considered as part of the Human Factors design criteria. The read across from merchant ship practice in other aspects of naval ship design, through for example the adoption of classification society's "Naval Ship Rules" (Ref. 17), shows that these two formerly separate design communities are already learning from each others practice to, hopefully, the benefit of both parties and the end user at sea.

In Mr **Rusling**'s discussion of weightings, function groups and vessel performance he overlooks an important aspect of the HPM. It is not only a discriminating tool but also a diagnostic tool. While the weightings allow the user to emphasise the parameters that they consider to be of greater significance in producing the overall VP, the technique does not only produce an overall VP score but also a scenario score for each ES and a FG score for each ES. By exploring these values for the vessel with best overall VP it is possible to identify the factors which reduced the performance of the vessel. Indeed, the user can even bore down into the individual components of the HPM and determine which performance measures (PM), associated with a particular ES and FG, led to the poor performance. If considered necessary, these factors can then be addressed, with the suggested solution, again, being evaluated through the HPM. In this way a winning design can be made even better.

Furthermore, Mr Rusling questions the benefit of using weightings in the approach presented. We would not wish to imply that the weightings presented, by way of showing the approach to assessing the simulations, are absolute or the only basis for design decisions. However, there is a need to present and manage the insights provided by the personnel movement simulations provided by such a tool as maritimeEXODUS, in exploring different ship operations and configurations. This does mean that a comprehensive exploration of a full range of Evaluation Scenarios are required if the full usage of a proposed configuration is to be explored. This is a dauntingly large exercise, and to some extent justifies the recourse to weightings to aid the information revealed. However, it may not be necessary in the future for every evolution to be investigated for every variant in ship configuration, but there is an initial need to build on the demonstration of principle presented here by a systematic application of the approach, either to possibly another extant design or to a new ship design. This would provide a benchmark for subsequent design teams and suggest where critical issues need to be addressed.

Mr Rusling is also right to draw attention to the slightly too all inclusive sense behind the VP term. Essentially it is short hand for "Vessel Performance, in the specific sense of personnel movement" and is not intended to be the only measure of merit for design decision. As with the selection of weighting values, it is primarily an indicator of performance, and one that both needs to be used with a sensitivity check and as a means of highlighting where there may be problems. In both cases the designer can interrogate the more detailed information to ascertain the likely "sore thumbs" or where more detailed investigation might be required. So there is no acceptable VP number. The process, like so much that is analytical in ship design, is essentially comparative and is to be used for the guidance of wise designers.

Thus it is essential to re-emphasise that the VP is a comparative measure, not an absolute measure. However, “acceptable” values for the VP can be suggested for a particular class or type by comparing the VP for a proposed new vessel designs with the VP derived from the current front line vessel of the same or similar type. The VP for the existing type then sets the standard by which all proposed competing designs can be measured. For the proposed design to achieve superior human factors performance, the “acceptable” VP to be achieved should be set lower than that for the existing design.

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## **G.2 - Guidance on the Design of Ships for Enhanced Escape and Operation**

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Industrial Partner: Directorate of Sea Systems, Defence Equipment and Support  
organisation of the UK Ministry of Defence (DES-SESea)  
Final Report to the (EPSRC)

### **BACKGROUND / CONTEXT**

Traditionally, when designing a ship the driving issues are seen to be powering, stability, strength and seakeeping. When the broad form of the layout has been finalised, human factors issues related to crew numbers, ship operations and evolutions, such as evacuation, are either ignored, considered as an after thought or incorporated through a set of prescriptive rules. This can result in significant operational inefficiencies and potentially hazardous environments onboard. Today, demonstrating compliance with evacuation requirements is compulsory for merchant ships, as set by IMO regulations, and is usually achieved through the use of sophisticated evacuation simulation software, such as maritimeEXODUS. However, this analysis is undertaken within the overall constraints of a finalised ship design and so cannot substantially influence the design. Furthermore, there is no agreed method of identifying and measuring the performance of the vessel under important normal operations (NOP) scenarios, nor is there a methodology for determining the overall human factors (HF) performance of the vessel i.e. incorporating both evacuation and NOP HF performance.

The most significant of the stages of ship design is preliminary design, when the major decisions are made as to the characteristics of the product and so the analysis of crew or passenger movement must be integrated with the design process to have an influence on the ship design. Thus a methodology, composed of a set of software tools (PARAMARINE-SURFCON and maritimeEXODUS) and a procedure for using them effectively, is required to fully integrate the analysis of personnel movement, in a wide range of scenarios, into preliminary ship design. The Design Building Block approach, implemented in the SURFCON-PARAMARINE software, permits an integrated initial synthesis that brings together numerically based sizing, hullform selection and, most significantly, the stylistic and configurational aspects crucial to evaluating human factors issues early in design. These are integrated in a single software package that utilises an information rich graphical user interface, greatly enhancing the ability of the designers and stakeholders to evaluate the performance of the design. The maritimeEXODUS personnel movement simulation software is capable of simulating both the evacuation and non-emergency circulation of large numbers of people within a variety of complex enclosures. The simulation model incorporates a wide range of factors, such as passenger behaviour, smoke and fire and the heel of the vessel. Significantly in the context of NOP scenarios, the individuals modelled in the simulation can be assigned specific tasks, so allowing the evaluation of complex procedures such as those that might be expected on a naval vessel.

## KEY ADVANCES AND SUPPORTING METHODOLOGY

The two academic partners provided complimentary expertise and access to the necessary software essential for the success of this project. Expertise in naval ship design and in the use of the PARAMARINE-SURFCON tool for the early stage design of ships was provided by UCL, while UoG provided its personnel movement expertise and its maritimeEXODUS personnel movement simulation software. The industrial partner provided the all important end-user requirements and expertise in the operation of warships.

The partnership achieved all objectives, as stated in the original proposal, demonstrating the viability of the methodology and the benefits that can be derived through its use. Further development in the methodology is anticipated through application to specific projects with the industrial partner. Key significantly novel advances made in the project include:

- The use of simulations to evaluate personnel movement applied in the earliest stages of ship design.
- The evaluation of personnel movement extended to include non-emergency scenarios.
- A transparent and reproducible methodology developed to determine overall HF performance of a given ship design and shown to be both discriminating and diagnostic.
- Guidance provided on the level of design definition necessary to carry out personnel movement simulations in preliminary ship design.
- The project provided insights to ship designers on specific features that either enhance or restrict personnel movement onboard heavily populated vessels.
- The project indicated those research areas that remain to be addressed for the comprehensive simulation and assessment of personnel movement in non-evacuation scenarios onboard ships.

Figure 1 illustrates the overall relationship between the expertise domains and software tools on which each research partner led. This shows, in flowchart form, the design and analysis activities that were carried out in each of the tools. The interface tools developed in this project were separate from the PARAMARINE-SURFCON and maritimeEXODUS software and permitted the required information to be transferred between them.

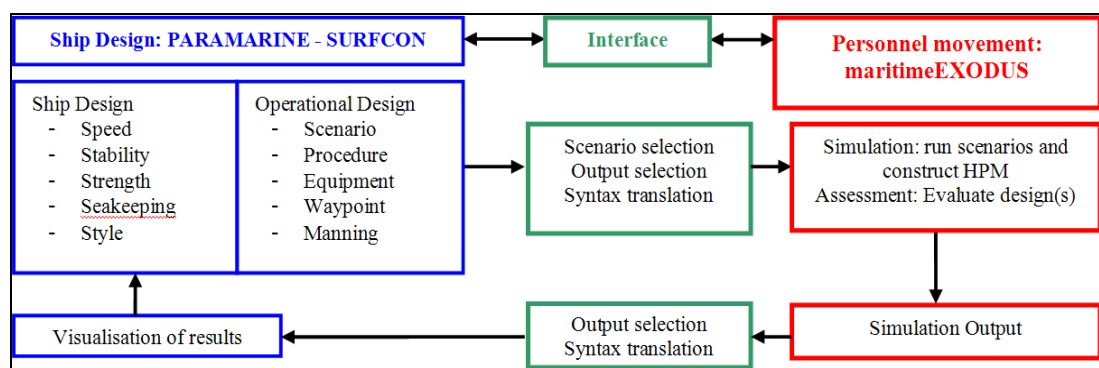


Figure 1: Flowchart showing the activities carried out in each of the main tools used in the project.

Achievement of each of the objectives, stated in the original proposal, are outlined below.

**1. To explore the impact on naval ship configurational design of issues associated with crew manning numbers, function and movement.**

This overall aim covers two distinct aspects investigated - the impact on the naval ship design process of the availability of personnel movement simulations in the early stages [1, 5] and the changes to the configurations that should be adopted based on the results of those analyses. The first of these aspects was extensively investigated using a new methodology, which was demonstrated through meaningful analyses able to be made at an early stage and incorporated into the design process. The second aspect was investigated by the investigation of the primary access route configuration - a major layout feature (see objective 5 for further details).

**2. To identify key performance measures for successful crew performance in normal and extreme conditions.**

The only agreed guidelines for evaluating HF performance of ship design relate to evacuation (i.e. time to muster and levels of congestion) and so conclusions drawn concerning the overall suitability of a ship design by one naval architect can be quite different from those of another. The complexity of the task grows as the size and complexity of the vessel increases and as the number and type of evaluation scenarios considered increases. The challenge addressed here was the development of a procedure that allows accurate, rapid, transparent and reproducible assessment of HF issues associated with vessel layout and crew operating procedures.

The unique technique developed to address these issues is known as the Human Performance Metric (HPM) [3, 6-10]. The HPM works by systematically evaluating one layout design against another, whether two variants of the same design or two completely different ship designs. The methodology involves defining a range of relevant Evaluation Scenarios (ES) against which the vessel will be tested. In order to gauge vessel HF performance across a range of criteria, the ES are made up of both evacuation and NOPs scenarios. The nature of the scenarios are dependent on the type of vessel. For the surface combatant vessel used as the exemplar in this project, some seven scenarios were identified, three evacuations: Normal Day Cruising A, Normal Day Cruising B, Action Stations and four NOPs: Blanket Search, State 1 Preps, Family Day A, Family Day B [8, 9]. In addition to defining the ES, a range of Performance Measures (PM) are defined to measure various aspects of personnel performance in undertaking the tasks associated with the ES. Examples of PMs for evacuation and NOP scenarios include; the time required to complete the assembly process and the total number of water tight doors (WTD) operated during the scenario [3, 6-10]. The PMs are determined through evaluating the output produced by the maritimeEXODUS simulation software, or its equivalent. In total some 32 PM [8, 9] have been defined for the selected surface combatant. Both the ES and PM were defined in consultation with our collaborating partners, the Ministry of Defence (MoD).

The suitability of the vessel layout is then evaluated for fitness of purpose through a combination of the PMs resulting from the execution of the ES. The numerical values generated by the PMs for each ES are arranged to produce the HPM. The

overall vessel HF performance is then determined through a weighted summation process of the various elements within the HPM [6-10]. Clearly, the HPM will be specific to the type of vessel being investigated, thus an aircraft carrier will have a different HPM to a submarine. However, the underlying concept of the HPM is common to all types of vessels and some components that make up the HPM may be similar across different vessel types. Using the HPM technique it is now possible to systematically evaluate the HF performance of a vessel in a manner which is reproducible and transparent and which provides both discriminating and diagnostic information [8-10].

### **3. To extend the ship evacuation software maritimeEXODUS to include additional non-emergency simulation capabilities.**

The maritimeEXODUS software forms the core of the HF evaluation component of the system. This software was specifically designed to simulate evacuation scenarios and, as part of this project, its capabilities were extended to include the simulation of the NOP scenarios, as identified under Objective 2 above. This capability built on an existing feature known as the Itinerary List (IL). Using the IL it is possible to assign crew (and passengers) a list of tasks to perform. As part of this project a range of new tasks were developed including: 'Terminate' command, used in the NOPs scenarios, allowing crew to stay at their last location once a task has been completed; 'Repeat' command, used to allow crew to repeat predefined set of tasks a number of times as is required in the patrol task; 'Search Compartment' command, which instructs crew to enter a list of assigned compartments to undertake a search as part of the blanket search scenario; 'Close Door' command, which instructs a crew member to check that a door has the correct status for the current ship state and, if not, change the status of the door; 'Give' and 'Receive' command, allowing a senior member of the ship's staff to issue tasks to lower ranked members, who 'Receive' the task [6-9].

In addition to these capabilities, a range of other modifications and additional software have been developed including:

- a) A separate utility program was developed (the Human Performance Metric Analyser) which automatically constructs the HPM matrix of human performance scores from maritimeEXODUS output that are used in the evaluation of the vessel design.
- b) The process of building vessel geometries ready for analysis was automated. Previously, the process of preparing a geometry could take as much as two weeks to complete, with the automation the majority of this process can now be completed within half an hour (based on the Type 22 Batch III Frigate exemplar).
- c) A new scripting language (SSF) was developed which enables third parties to easily set up a population and their itineraries within maritimeEXODUS without the need to navigate through a complex user interface, reducing a considerable amount of tedious time consuming effort.
- d) Additional output files were required from maritimeEXODUS in order for it to interact with the ship configuration software SURFCON. These include images of contour maps displayed within maritimeEXODUS showing the locations of severe congestion and footfall maps. Animated output files were also implemented in order to illustrate individuals moving around the design.



**4. To extend the ship design software so that it can provide a modelling environment that interactively accepts maritimeEXODUS simulation output for a range of crew evolutions.**

The original proposal anticipated making changes to the PARAMARINE-SURFCON software to allow the interactive display of processed results from the maritimeEXODUS simulations. This focussed on the "visualisation of results" activity shown in Figure 1. The purpose of this functionality was to place the numerical data generated by the simulations into the context of the spatial configuration of the ship design, enhancing designer understanding of the results and aiding subsequent decision making. The early development work identified the changes that needed to be made to the PARAMARINE-SURFCON software to provide the desired functionality. The main enhancement proposed was the ability to display both static and animated two-dimensional texture maps, containing graphical representations of the maritimeEXODUS simulations, overlaid onto the three-dimensional CAD representation of the ship. The possibility of adding new output file formats (or enhancing those that already existed) was also considered. The early research also investigated alternative third-party visualisation tools and approaches that could be used to illustrate the desired functionality. Subsequent discussions with GRC (the vendor of PARAMARINE-SURFCON) indicated that the time required to make the necessary modifications was beyond the scope of the project and so this option was not pursued. Further discussion with GRC has suggested that the modifications proposed are possible and GRC is now keen to implement them as part of the ongoing development of the software (E-mail Dr Fowler, General Manager of GRC October 2007). Meanwhile, the UCL research team developed alternative visualisation techniques to be used in the current research project. These visualisations were divided into three main types, each of which was addressed in a different way:-

- a) Tabular data: Certain data produced by the HPM (see figure 2), is best represented in tabular form and this was viewed in a spreadsheet tool and by adapting the spreadsheet functionality already existing within PARAMARINE.
- b) Graph data: Other data was best represented by line graphs, and this was illustrated by adapting the range of 2D graph functionalities available within PARAMARINE.
- c) Graphical data: In order to fully place the personnel movement numerical data into the context of the vessel configuration, some data needs to be represented in 3D, and this was implemented using the VRML 3D modelling language. Although this required a free third-party viewer to be used and was not integrated with the PARAMARINE-SURFCON model of the ship, a level of interactivity was provided allowing the designer to investigate the extensive numerical data.

Another aspect of this functionality was the UoG developed 'HPM Analyser', which reads the results of maritimeEXODUS simulations and generates output files read by PARAMARINE and displayed and interrogated by the naval architect. In addition, the output files from maritimeEXODUS and the HPM Analyser can be read by newly developed translation software and converted to VRML.

### **5. To demonstrate a methodology for ship design that integrates ship configuration design with modelling of a range of crewing issues through PARAMARINE-SURFCON.**

The method developed in the research project consisted of taking existing and developed software tools, which are then used for personnel movement analysis at the early stages of ship design. The methodology is broadly described in terms of these software tools by Figure 1. The key features of the developed methodology are:

- a) A procedure for modelling design features crucial to personnel movement analysis in PARAMARINE-SURFCON: Modelling techniques and standards were developed to allow the definition of design details, such as doors, hatches and ladders, and of the Watch and Station Bill (W&SB), which contains all the necessary information on the locations of the ship's crew for each operating condition.
- b) A procedure and software tools for transferring PARAMARINE-SURFCON ship definition models to maritimeEXODUS: A tool was developed to convert the existing PARAMARINE-SURFCON output files into a format accepted by maritimeEXODUS and the new 'scenario generator' program.
- c) Enhancements to maritimeEXODUS: These enhancements included new commands and a scripting language outlined under Objective 3 above.
- d) A procedure and software tools for viewing, investigating and transferring maritimeEXODUS simulation results to PARAMARINE-SURFCON: The use of existing PARAMARINE-SURFCON functionality and third party tools to allow visualisation of the results is outlined under Objective 4 above.

The procedure developed can be summarised in the following steps:

1. Model the balanced ship design using the Design Building Block approach (see original Case for Support).
2. Populate the model with personnel movement oriented design features and define the W&SB.
3. Output definitions of the geometry, connectivity and operational design using existing outputs (DXF and KCL).
4. Translate KCL to maritimeEXODUS and scenario generator input format (NMTA) using spreadsheet tool.
5. Input NMTA and DXF files into maritimeEXODUS, mesh the model and generate scenarios.
6. Run 50 simulations and perform analysis to produce HPM.
7. Output files for the required scenarios: images, videos, and graphs plus the whole HPM in KCL and CSV format.
8. Import the KCL into PARAMARINE to visualise results using graphs and tables.
9. Translate HPM file and links to images and videos into VRML format for interactive 3D display of results.

The procedure and software tools were demonstrated by application to the Type 22 Batch III Frigate design. This class is currently in service with the Royal Navy and MoD provided numerical and geometric information.

In addition to producing a higher than normal resolution PARAMARINE-SURFCON model of the design as built, several variant models were produced for assessment:

- a) Variant 1, High Resolution: Model of the design as built, with detailed configurational and numerical data.
- b) Variant 1, Intermediate Resolution: Model of the design as built, but with a simplified representation of the layout more appropriate to preliminary design.
- c) Variant 1, Very Low Resolution: Greatly simplified model of the design as built, with only the basic internal subdivision (decks, watertight compartments, doors and damage control zones) represented, to scope Variant 1 (IR).
- d) Variant 2, High Resolution: A variant using two side passageways in place of the single centreline passageways on No. 1 and No. 01 Decks of the baseline, with detailed configurational and numerical data.
- e) Variant 2, Intermediate Resolution and Variant 2, Very Low Resolution.

Each of these was a balanced ship design, assessed for feasibility in the traditional naval architectural performance areas, such as stability and powering. Importantly, they all used the same crew breakdown and W&SB for 262 ship's staff, given the generation of a representative W&SB was vital to perform personnel movement simulations. This range of models assessed a major design feature in ship layout and personnel movement - the arrangement of the main passageways - and importantly assessed the effect of the use of different levels of detail, particularly the reduction in detail to a level more representative of that likely in preliminary ship design.

Evaluative scenario	Scenario Weight	Variant 1	Variant 2
Normal Day Cruising A	1	46.15	44.94
Normal Day Cruising B	1	47.74	48.78
Action Stations Evacuation	1	46.69	49.78
State 1 Preps	1.5	66.63	76.60
Blanket Search	1.5	80.33	84.74
Family Day A	1.5	44.80	49.81
Family Day B	1.5	53.04	57.89
Overall Performance of design		507.8	547.1

Figure 2: HPM for Variant 1 (with additional ladder) compared with Variant 2. Design with the lower score is the superior one.

After analysing the HPMs, it was found that the single passageway Variant 1 design just marginally outperformed the double passageway Variant 2 design. Thus the HPM technique was able to discriminate between two competing designs and identify which produced the superior HF performance, based on the selected evaluation scenarios and performance measures. Analysis of the HPMs for the very low resolution early design configurations also suggest that Variant 1 was marginally the superior layout overall, although the actual HF performance differed markedly for different scenarios. Thus for Variant 1, State 1 Preps was the best performing scenario and Action Stations evacuation scenario was the worst performing scenario. This suggests that when using early design configurations, the ES and PM contributing to the HPM need to be slightly modified, reflecting the lack of HF relevant detail likely to be available on the design.

Detailed examination of the results demonstrated that the State 1 Preps scenario was the best performing scenario, for Variant 1, while the Action Stations evacuation scenario was its worst performing scenario. Once the better configuration had been identified, the HPM was then used, in diagnostic mode, to determine if that design could be further improved. Thus further interrogation of the HPMs, revealed considerable congestion developed during the Variant 1 evacuation scenarios. These results suggested that the congestion levels could be reduced through the introduction of a strategically placed single ladder between No. 2 and No. 1 Decks. The ladder was added to the design and the Variant 1 simulations re-run producing an updated HPM. Analysis of the updated HPM revealed that the modified Variant 1 design now out performed Variant 2 by some 8%, as shown in Figure 2, demonstrating the diagnostic capabilities of the methodology [6-8, 10].

There are several key points regarding the development of the methodology:

1. A practical procedure and toolset was developed for analysing personnel movement in the early stages of ship design.
2. The production of a representative W&SB should be part of preliminary ship design, so that any changes due to simulation results can be reflected in future designs.
3. The HPM technique was able to discriminate between two competing layouts and to identify which produced the superior HF performance, based on the selected evaluation scenarios and performance measures.
4. The HPM technique is applicable to both detailed design definitions, based on as built features, and the less detailed models, more typical of preliminary ship design.

## **PROJECT PLAN REVIEW**

The programme outlined in the original proposal described three main phases of the project - development, integration and demonstration. As the project evolved it became apparent that more effort was required on the development phase than had been anticipated, primarily in the acquisition of data for and development of the detailed ship design models, maritimeEXODUS simulation software enhancements and the development of the HPM (defined under Objectives 2-4). In addition, the initial concepts for the integration of the two tools via modifications to PARAMARINE were not possible, and so alternative methods of integration were used (see Figure 1). The adaptations needed to overcome these challenges lead to a reduction in the extent of the demonstration activities in the later stages of the project. However, it was still possible to demonstrate the application of the approach and the functionality of the enhanced software tools developed during the project.

Sixteen formally minuted meetings were held over the course of the project, covering management and technical issues. Seven of these included a representative of the industrial partner (MoD). The industrial partner also received extensive progress reports at the end of each of the three years. There were also technical meetings between the individual researchers at the two institutions on a frequent basis and with the industrial partner as required.

## RESEARCH IMPACT AND BENEFITS TO SOCIETY

This project is the first example of research into the extension of personnel movement simulation from evacuation into the much wider problem of personnel movement in operational scenarios. Secondly this extension has been applied to preliminary ship design, when the ship configuration is being initially determined. The open ended extensible approach pioneered in this project will offer a number of advantages through being incorporated in preliminary ship design. This project has resulted in the following significant developments:

- A novel methodology, known as the Human Performance Metric (HPM), has been developed that allows, for the first time, accurate, rapid, transparent and reproducible assessment of Human Factors (HF) issues associated with vessel layout and crew operating procedures. The technique provides an overall measure of HF performance encompassing both emergency and normal operations conditions. Use of the HPM will lead to safer and more efficient vessel design.
- The HPM concept has been incorporated into the ship design cycle through linking the maritimeEXODUS software with the PARAMARINE-SURFCON software. In this way vessel designs can be assessed for HF performance in the earliest stages of ship design cycle. This enables the identification of areas of poor design leading to poor HF performance early in the design cycle where changes can be made quickly, easily and hence cheaply. Through the life time of a naval vessel, personnel costs, in part dependent on early layout decisions, far exceed the capital cost of the vessel, thus using this approach to improve procedures and, potentially, reduce crew size can lead to considerable savings in through life costs.
- The HPM methodology also provides fleet operators with a consistent and verifiable method for setting HF design objectives for new vessel concepts and evaluating proposed designs.
- The HPM methodology and the linkage to ship design software can be applied to other types of vessel, such as passenger ships. This will lead to the design of safer and more efficient passenger vessels.
- The HPM methodology can be applied to other industries, in particular the building industry allowing the assessment of HF issues associated with the design of buildings, terminals and the layout of large public events.
- This research has had strong academic content, with two of the project team currently writing up their PhD dissertations based on the work produced for this project (Mr S.J. Deere - HPM concept and Mr L. Casarosa - HF Integrated into the ship design cycle).

## EXPLANATION OF EXPENDITURE

The overall expenditure on the project was in line with the allocated budget. There was a slight increase in salary costs at UoG as more than the allocated 75% of Dr Lawrence's time was required on the project. The difference was made up by funding from UoG.

### Further Research and Dissemination Activities

The work undertaken in this project has contributed to 11 publications in journals and conferences. Further details on these can be found on the project web sites: <http://fseg.gre.ac.uk/fire/ego.html> and <http://www.ucl.ac.uk/~ucemrgp/gdseeo.html>. These included presentations at eight international conferences in Belgium, Italy, Germany, Korea and the UK, including an invited key note address at a conference in Canada. Two further journal publications are under preparation and will be submitted to the SFPE Journal of Fire Protection Engineering and the SNAME Journal of Ship Research. Papers will also be submitted to several conferences including IAFSS Germany 2008 and the 5th RINA HF Conference. Results from the project have also been disseminated to students on the Master Training Programme in Computational Science and Engineering at Greenwich (see <http://cse.gre.ac.uk/>) and will be presented to the Masters in Naval Architecture at UCL (<http://www.mecheng.ucl.ac.uk/learning/graduate/msc/naval-architecture/>). Results from the project will also be discussed at an international short course on evacuation simulation at the University of Greenwich in April 2008 (see [http://fseg.gre.ac.uk/fire/course1.html#short\\_course\\_intro](http://fseg.gre.ac.uk/fire/course1.html#short_course_intro)).

Future proposals are currently being written between the partners. A follow on EPSRC project is under investigation that will focus on applications of the HPM to passenger vessels. Also under investigation is a proposal focusing on current new MoD ship design projects. This will again involve close collaboration between the partners in this project and funding is being sought directly from the MoD. The University of Greenwich markets the maritimeEXODUS software internationally. The new features and capabilities developed for the maritimeEXODUS software will be incorporated into the next release of the software, further improving the software's unique position in the market place. The enhancement of PARAMARINE-SURFCON in regard to HF simulation interfacing now intended by GRC Limited is a direct result of the prototyping undertaken by UCL in this project. This will then be made available to PARAMARINE's many users in the UK ship design community.


### Papers Published or Awaiting Publishing

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2. Andrews, D J, Pawling, R and Casarosa, L, "Integrating Ergonomics into Ship Design", CETENA Human Factors Conference, Genoa, October 2005, Proceedings on CD; copy held by UCL.
3. Andrews, D J, Pawling, R, Casarosa, L, Galea, E R, Deere, S, Lawrence, P, Gwynne, S and Boxall, P, "Integrating Ship Design and Personnel Simulation", INEC, IMarEST WMTC, London, 6 - 10 March 2006, Proceedings on CD, ISBN 1-902536-54-1.
4. Andrews, D J, Casarosa, L and Pawling, R, "Integrating the Simulation of Operations Into Preliminary Ship Design", NAV 2006; International Conference on Ship and Shipping Research, Genoa, 21 - 23 June 2006, Vol. 1, pp 4.3.1-4.3.12.
5. Andrews, D J, "Simulation and the Design Building Block approach in the design of ships and other complex systems", 2006 Proc. R. Soc. Vol. 462, pp 3407-3433.
6. Andrews, D J, Pawling, R, Casarosa, L, Galea, E R, Deere, S and Lawrence, P, "Integrating Personnel Movement Simulation into Preliminary Ship Design", RINA Int. Conf. on Human Factors in Ship Design, London, 21-22 March 2007, pp 117-128.
7. Andrews, D J, Pawling, R, Casarosa, L, Galea, E R, Deere, S and Lawrence, P, "Integrating Personnel Movement Simulation into Preliminary Ship Design", RINA IJME, to be published Vol. 150 Part A1 2008.
8. Galea, E R, "The next step in the rise of maritime human factors simulation models : Optimising vessel layout using human factors simulation", Key Note Address, The Rise of Maritime Simulation, Ocean Innovation 2007, Halifax, Canada, 21-24 Oct 2007. ([http://www.oceaninnovation.ca/OI-2007\\_guide\\_low%20res.pdf](http://www.oceaninnovation.ca/OI-2007_guide_low%20res.pdf)).
9. Deere, S J, Galea, E R and Lawrence, P, "A Systematic Methodology to Assess the Impact of Human Factors in Ship Design", Applied Mathematical Modelling, to be published Vol 32, 2008 <http://dx.doi.org/10.1016/j.apm.2007.12.014>
10. Deere, S J, Galea, E R and Lawrence, P, "Optimising Vessel Layout using human factors simulation", Pedestrian and Evacuation Dynamics 2008, 27-29 Feb 2008 Wuppertal, Germany, To appear 2008.
11. Deere, S J, Galea, E R and Lawrence, P, "Assessing Naval Ship Design for Human Factors Issues Associated with Evacuation and Normal Operations", COMPIT08, 21-23 April 2008 Liege Belgium, To appear 2008.
12. Andrews, D J, Casarosa, L and Pawling, R, "Interactive Computer Graphics and Simulation in Preliminary Ship Design", COMPIT08, 21-23 April 2008 Liege Belgium, To appear 2008.

## Reports from Project Partners


A letter from MoD (DES SESea), dated the 18th of January 2008, is included.

UNCLASSIFIED



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Please reply to:  
  
 Our Reference:  
 D/STG/198/2/1  
 Date: 18 Jan 2008

*Dear Professor Andrews,*

**Guidance on the Design of Ships for Enhanced Escape and Operation – 'Project EGO'**  
**EPSRC funded project 2005-2007**

1. The Ship Design Section of the Directorate of Sea Systems (formerly Sea Systems Group) has been the industrial partner with University College London and the University of Greenwich (UCL/UoG) on Project EGO. The research project has been completed to the full satisfaction of the Section.
2. All deliverables required under the supporting contract have been completed by UCL/UoG. Timely delivery of comprehensive project milestone reports along with presentations by the research team have been informative, allowing close monitoring of the project and discussion of emergent research findings. The research team provided excellent liaison with the industrial partner.
3. The 5 main Project Objectives have been met, with clear evidence of such given in demonstrations and interim project reports.
4. The project has reached interesting conclusions in a number of areas:
  - (a) There is potential to use the methodology to investigate existing ship designs. There may be the possibility of using the behavioural matrix feature of *maritimeExodus* to quantify perceived 'good practice' in existing ships for a range of on-board operations, to produce 'Gold Standard' design guidance.
  - (b) The degree to which model maturity affects the outcome of personnel modelling appears to be more limited than currently perceived. This could be significant in early stage design analysis.
  - (c) Early in the project the research team identified the importance of accurate and realistic complement modelling for use with *maritimeExodus*. It became obvious that production of a suitable 'Watch and Station Bill' at an early stage of the project was going to be essential and this was achieved by the research team in conjunction with the industrial partner, significantly benefiting the latter stages of the project.
5. The original project aim was to demonstrate the feasibility of integrating personnel modelling into the early concept stage of ship design. The research has clearly demonstrated this is a valid hypothesis. There is much potential to use this now proven methodology as a tool in future research, to investigate current ships and the wider ship design process, and further develop design guidance.

*Yours,*

*Daniel McCarthy*

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